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1 **Perimeter Control as an Alternative to Dedicated** 2 **Bus Lanes - A Case Study**

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1 **ABSTRACT**

2 Dedicated bus lanes (DBL) are a common traffic management strategy in cities all over the world,
3 as they improve the efficiency of the transit system clearly by preventing buses from getting trapped
4 in traffic jams. Nevertheless, DBL also have certain disadvantages. In particular, they consume
5 space, reduce available capacity for general traffic, and can thus lead to even more congested car
6 traffic situations. Hence, it is appealing to find more efficient alternatives that maintain a sufficient
7 network supply for general traffic while guaranteeing high commercial speeds for the bus system.
8 To this end, this paper investigates if perimeter control (gating) can be such an alternative to DBL
9 strategies. This solution aims at controlling the traffic conditions of a given area by monitoring
10 vehicle accumulations and adapting traffic signals parameters to reach the targeted conditions. If
11 free-flow states can be maintained within the zone, then DBL become superfluous. This hypothesis
12 is examined through a simulation case study with an urban arterial acting as the targeted area. A
13 multi-scale approach is applied for the controlling, in order to take into account not only the ve-
14 hicle accumulation inside the area, but also the queue lengths at its perimeter, addressing thereby
15 one of the main issues associated with perimeter control schemes. Thanks to the gating strategy,
16 traffic performance in the arterial, measured through vehicle accumulation plus mean speed and
17 density, is improved significantly. Moreover, results show that bus operations reach almost the
18 same efficiency-level when DBL are replaced by perimeter control. At the same time, the avail-
19 ability of an additional lane for general traffic in the control case significantly increases the arterial
20 capacity for cars.

21 *Keywords:* Dedicated Bus Lanes, Perimeter Control, Urban Arterial, Transit Operation

1 INTRODUCTION

2 Traffic congestion and its negative impacts is an ongoing topic of discussion among city authorities
3 all over the world, and will continue to remain on the agenda as urban economic development (1)
4 and number of vehicles are increasing (2). Some regions (e.g. city centers) are predestined for
5 bottlenecks due to its function as junctions and economic hubs. Once congestion arises in these
6 sensitive zones, congested traffic states start to propagate in the surrounding network sections and
7 may lead to major gridlocks. Therefore, it becomes crucial to monitor and control in real-time
8 urban traffic conditions in order to utilize the existing network as efficiently as possible (3) and
9 minimize congestion hours in such critical regions.

10 Urban congestion has direct effects on both travelers (increased travel time, reduced speed,
11 decrease in time reliability, greater fuel consumption, higher wear, etc.) and the environment
12 (increased pollution and noise). In addition, traffic jams affect also other transportation modes, in-
13 cluding public transport. In particular, bus lines might experience increases in both, average travel
14 times and unreliability for passengers (4). As a result, the transit system loses appeal and the shift
15 of transportation mode from individual vehicles to massive transportation modes as emphasized
16 in (5) can decrease. Local authorities and operators are therefore compelled to deploy strategies
17 to improve performance and increase attractiveness of the public transport system, paying special
18 attention to bus operations.

19 A common measure deployed worldwide to reduce bus delays is the use of dedicated bus
20 lanes (DBLs), which protect bus operation from general traffic by reserving a special lane. Among
21 others, (6) and (7) emphasize various advantages of DBL, in particular the fact that they prevent
22 buses from getting trapped in traffic queues at signalized intersections, significantly improving
23 thereby the bus system performance. Nevertheless DBLs still remain controversial and not always
24 well accepted. Especially, (8) points to the unavailability of the dedicated lane for individual vehi-
25 cles as a main drawback, whereby capacity for cars is decreased. As a consequence DBL are only
26 appropriate for low traffic flows from a car user perspective (9, 10), a disadvantage that must be
27 taken into account. Research is ongoing in the field of DBLs. Pre-signals, as proposed by (11), can
28 be used to better use the intersection capacity even when bus flows are low; hence keeping the bus
29 priority and reducing the negative effects on cars. Intermittent bus-lanes, as proposed by (12), are
30 a further development. Thereby, DBLs are opened intermittently to general traffic in order to mit-
31 igate the negative effects of DBLs on car traffic while keeping bus operations optimal. However,
32 although IBL have been deeply analytically studied (8, 9), tentatives of real-world deployment re-
33 main very rare. On a larger scale, decisions for DBL deployment can also serve different purposes
34 like promoting the use of public transport by reducing space for cars, which makes it a matter of
35 political intentions.

36 The current paper proposes an alternative to DBL by applying the concept of *Perimeter*
37 *Control*, also known as *Gating*, to a sensitive region and replacing at the same time the bus lanes
38 in the area with general purpose lanes. More precisely, this approach is tested on an urban ar-
39 terial. Perimeter control as described by (13) addresses the mentioned point of increasing traffic
40 efficiency in a existing network. Basically, the idea of this control strategy is to restrict the input
41 flow to a predefined area, in order to maintain non-congested traffic states inside that region (14)
42 and improve thereby the overall traffic performance. Thus, congestion is relieved on the network
43 level. More exactly, the incoming flow is controlled through the traffic signals at the boundaries
44 of the "protected" area. One advantage of this approach is, that it can be implemented in real time
45 through real traffic data. There are various examples of perimeter control strategies in literature

1 with positive results, i.a. (13, 14, 15, 16, 17, 18, 19, 20). The strategy is successful when the saved
2 delays in the controlled region are higher than the additionally generated delays by the controller
3 at the entries. Perimeter control schemes are already applied in some cities. Zurich (19) or Chania
4 (3) can be mentioned as real examples. A main drawback of gating is that long queues can occur
5 at the perimeter entries, which lead possibly to spillbacks that affect the surrounding network (for
6 details see (14, 16)). Only a few papers focus more deeply on this issue. One approach can be
7 found in (20), where the queue length at the perimeter boundary are considered and controlled in
8 the model. (21) recently developed a so called multi-scale controller which takes the queue-lengths
9 at perimeter entries into account by integrating the occurring delay in the queues directly into the
10 objective function. Traffic performance is therefore improved globally by considering both the
11 network scale and the local level.

12 If a high level of service can be obtained through perimeter control, the original purpose
13 of DBL to guarantee free flow conditions for buses, becomes possibly redundant and DBL could
14 be eliminated. This hypothesis is examined in the following by applying a multi-scale feedback
15 perimeter controller as an alternative to DBL in a simplified simulation case study. In contrast
16 to former studies, a multi lane urban arterial is considered as the controlled perimeter instead of
17 a region. Similar to a city center, an arterial is often a traffic hot spot and a critical section for
18 congestion emergence. The control scheme is tested in particular in the context to bus operations,
19 as the travel times of buses are compared for cases with perimeter control and with DBL. Because
20 of the worldwide presence of DBLs, the current case study is of relevance and can provide decision
21 makers with new aspects, all the more since it strikes a new path by the complete replacement of
22 DBL in contrast to the optimization of DBL examined in former research.

23 The paper is organized as follows. After describing the simulation and controller frame-
24 work in Section 2, findings are presented in Section 3. This section starts by an evaluation of the
25 controller to validate that the framework developed for large-scale traffic flow models works with a
26 detailed description of traffic dynamics, i.e. in micro-simulation. Then, the controller can be safely
27 applied to study the opportunity of replacing a DBL by a gating strategy. Section 4 is devoted to
28 the conclusions.

29 **METHODOLOGY**

30 The concept for the multi-scale control approach applied in this work originates from (21), but
31 the original methodology has been adapted to address different research questions and objectives.
32 Especially, this method is adapted to a finest level of details, i.e. micro-simulation, whereas it
33 has been originally developed for large-scale models as the biggest part of existing papers. (21)
34 provides the accurate framework to implement and test in simulation a multi-scale control that aims
35 at maintaining a protected area in free-flow conditions while simultaneously limiting spillbacks
36 at the entries of the protected area. Different scenarios, presented in the next section, will be
37 simulated.

38 **Case Study**

39 All the simulations for the present work were executed with the traffic simulation platform *Symu-*
40 *Via*. *SymuVia* is a dynamic microscopic traffic simulator and provides thus a very high level of
41 detail. It is based on the kinematic wave model (KW) described by (22) as well as (23) with a
42 Lagrangian resolution introduced in (24). Multiples components to reproduce urban networks (in-
43 tersections, lane-changing, multi-class, etc.) are embedded in the simulator and the positions of all

1 vehicles are calculated every second giving access to their full trajectories. Furthermore, *SymuVia*
2 uses a dynamic traffic assignment based on users' equilibrium.

3 *Network*

4 Figure 1 gives an overview of the network-set up and of the controlled intersections in the case
5 study. The network consists of a 14 x 14 street grid, also known as a *Manhattan-type* network.
6 This layout is large enough to represent roughly a district of a city with its interlinked traffic
7 dynamics. In the center of the network, an arterial road crosses the whole district. All links are
8 200 meters long. The arterial has three lanes and is one-directional from west to east. The rest of
9 the links are bi-directional with one lane in each direction. The speed limit for the arterial is 50
10 km/h, and 30 km/h for the rest of the links.

11 Vehicles can enter and leave the arterial at any of its intersections. Only vehicles on the very
12 left lane can turn into a side-street on the left hand side and same holds equally for right-turning
13 vehicles. Vehicles entering the arterial from the side-streets have to take the nearest lane (i.e. most
14 left or most right lane). Once cars move on the arterial, they can switch lanes without restriction.

15 Two regions are denoted: the arterial is considered as a center region *A*, whose traffic states
16 should be controlled, the side streets represent the outer region *B*. On every intersection the total
17 cycle length of the signals is 60 seconds, and there is neither intermediate time nor a yellow phase.
18 Each cycle contains two phases, where the two opposite approaches belong to the first phase and
19 the arterial to the second. On side street intersections, green time is split evenly 30s/30s for both
20 phases. For arterial-side-street intersections, which are controlled later, the arterial gets assigned
21 40s of green time and the side street entries 20s of green time for the cases without control. Due to
22 the higher demand, the arterial has also a higher green-time ratio, which is assumed to be realistic
23 and consistent with the hierarchy of real urban networks. In total there are 14 intersections linking
24 the arterial with the outside region, on which the controller is applied via the traffic signals, i.e.
25 green times are updated at each control period.

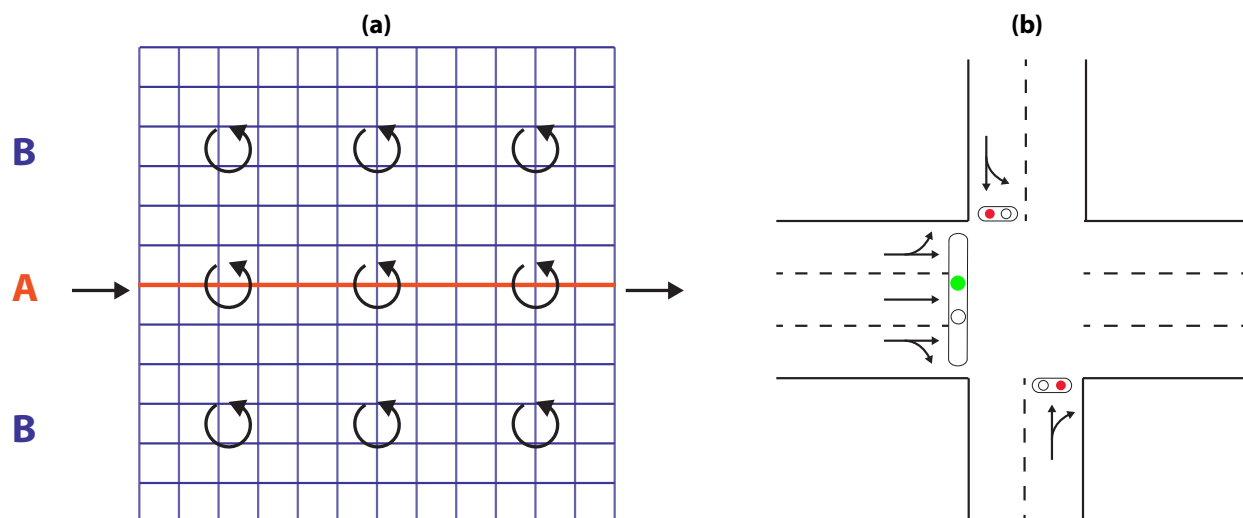


FIGURE 1 (a) Manhattan-type network with an arterial as the controlled region A and the outer region B. Arrows represent inner and outer demand. (b) Schematic intersection arterial - side street with controlled traffic signals and traffic streams

1 Demand

2 There are two types of demand. First, there is an outer demand entering and leaving the network
 3 through the arterial and passing the network from left to right. Second, there is an inner demand
 4 with both, origin and destination within the network. To generate this demand, the network is
 5 divided into nine zones of equal size and a demand-level is defined for the number of vehicles
 6 traveling from each zone to each other zone. The arterial (outer) demand is fixed to 2600 veh/h,
 7 while the zone-to-zone (inner) demand varies over time with the intention to simulate a typical
 8 peak period - 300 veh/h during the first 30 minutes, 600 veh/h during the second 30 minutes, and
 9 300 again veh/h during the last 30 minutes. A simulation run lasts 90 minutes.

10 Multi-Scale Feedback Control Approach

11 The controller is feedback-based, which means that the control action is dependent on the pre-
 12 vious output. It is worth noting that the proposed methodology can be used with other control
 13 schemes. Traffic detectors (sensors) measure indirectly the control variable J_D (total time spent)
 14 while the traffic signals parameters (actuator) influence the control variable (green time ratios for
 15 every perimeter intersection). The detectors are placed on every street entering and leaving the
 16 arterial. As mentioned, the challenge of the multi-scale control algorithm are the two competing
 17 control objectives, which need to be coupled into an integrated control scheme (21). The traffic
 18 performance should be optimized simultaneously at the network and the local level. As indicator
 19 for the global traffic state in the protected perimeter we use the total vehicle accumulation in region
 20 A. For the local level, the total delay, which is directly related to the queue lengths, at the entry
 21 intersections are considered as indicators. Traffic conditions are monitored through virtual detec-
 22 tors which give access to the total vehicle accumulation of the zone as well as to queue lengths
 23 at the entries. Notice that accumulation is directly connected to the total time spent by vehicles
 24 inside the arterial. The applied controller calculates the optimal green time ratios for every entry

1 intersection, based on the measured data, in order to optimize the two objectives mentioned above.
 2 The new green time ratios are updated and the traffic signal parameters are specifically modified at
 3 each intersection every K seconds. This implies that one control period lasts K seconds. To change
 4 signal timing more often seems not realistic in this context as cycle length on intersections is 60
 5 seconds for our case study.

6 The optimization problem is formulated and explained by the following equations, where
 7 (1) is the objective function and equations (2) - (10) are the constraints. Note that the dependence
 8 of variables to the time period may be omitted in the following formulation to make the writing
 9 easier.

$$\min J_D = \sum_{p=1}^L \left(K * (n_{AA} + n_{AB}) + \sum_{i \in I} \sum_{m \in M \setminus M_{out}^i} x_m^i * k_x * \frac{c - g_m^i}{2} * \frac{K}{C} \right) \quad (1)$$

s.t.

$$n_{AA}(k+1) = n_{AA}(k) + \lambda_{Arterial 0} \cdot K - \lambda_{Arterial 14} \cdot K \quad (2)$$

$$n_{AB}(k+1) = n_{AB}(k) + \lambda_{BA} \cdot K - \lambda_{AB} \cdot K \quad (3)$$

$$\lambda_{BA} = \sum_{m \in M \setminus M_{out}^i} \mu_m^i \quad (4)$$

$$\lambda_{AB} = \sum_{m \in M \setminus M_{in}^i} \mu_m^i \quad (5)$$

$$\mu_m^i = \min\{q_m^i, (s_m^i * g_p^i)\} \quad (6)$$

$$x_m^i = \frac{u * w}{u + w} * (c - g_m^i) * \frac{q_m^i}{(q_{max} - q_m^i)} \quad (7)$$

$$q_{max} = \frac{u * w}{u + w} * k_x \quad (8)$$

$$g_{p,min}^i \leq g_p^i \quad (9)$$

$$g_{p,max}^i \geq g_p^i \quad (10)$$

10 In the objective function (1), the total travel costs J_D are minimized. These travel costs are
 11 composed of (i) the total time spent by vehicles in region A (arterial) during one control period,
 12 i.e. the first two terms multiplied by the length K of the control period, and (ii) the total delay at
 13 the different entry intersections. According to KW theory, this delay is calculated as the product
 14 of the queue length x_m^i with $k_x * \frac{c - g_m^i}{2} * \frac{K}{C}$ where k_x is the jam density, g_m^i is the green time for
 15 stream m at intersection i , c is the cycle duration and $\frac{K}{C}$ is the number of traffic signal cycles during
 16 one control period. The queue lengths in outflowing direction are not taken into consideration
 17 here, as they are accounted for when computing the accumulations in the protected region. Note
 18 that the two objective criteria have the same weight, which can be adjusted for different purposes,
 19 according to the corresponding main aim, see also (25). Constraints (2) and (3) stand for the vehicle
 20 accumulation in region A, which is basically inflow minus outflow. The predefined flow entering
 21 and leaving region A through the arterial is simple to measure with loop detectors. Meanwhile the
 22 flow that enters and exits of region A through the side streets is the sum over all intersections ((4)
 23 and (5)). This flow must be the minimum of the measured demand on the upstream loop detectors

1 and the capacity of the entry (6)). The capacity however depends on the allocated green time for the
2 entry and changes therefore with every control cycle. Equation (7) shows how mean queue lengths
3 during one period are estimated based on KW model, taking into account the measured arrival
4 flow, the green time and the link capacity (8). Contrary to (?), we decide to express the length of
5 the queue in terms of distance. Because the controller is based on a detailed description of traffic
6 dynamics, it makes it possible to precisely track the propagation of the queue. To this end, virtual
7 loop detectors have been emulated at the entry of the approach links, giving access to the average
8 demand q_m^i during one control period. This value that is then used to derive the average length of
9 the queue for the control period. If the queue cannot disappear during the control period, equation
10 (7) will underestimate the length of the queue until the queue spills back on the detector located
11 at the entry of the approach link. Consequently, queue lengths are approximated during transition
12 phase. Moreover, it is important to notice that, in the case of strong spillbacks, equation (7) strongly
13 underestimates the length of the queues and the associated delays in the objective function (1).
14 However, in such a case, a DTA process will be required because congestions spreading on region B
15 will have an impact on route choices and traffic assignments. Consequently, the controller propose
16 here is valid only when the queues can be maintained within the approach links. Validated by
17 visual inspection of the simulated results, the assumption seems appropriate and this analytical
18 formulation gives an accurate average estimation of the queues' lengths. Furthermore a minimum
19 and maximum allowed green time-ratio for the entries is defined by (9) and (10). These boundaries
20 were defined to emulate realistic scenarios. It seems not plausible to have green durations below
21 six seconds. Same holds for the maximum boundary. If the red sequence for the high-demand
22 arterial becomes too long, this leads immediately to spillbacks. Note that, for an overview, table 1
23 lists the used variables.

TABLE 1 Nomenclature

Variable	Description	Value (if constant)
J_D	Total travel costs	
K	Control period [s]	300
k	Index of the current control period	
$n_{ab(k)}$	Calculated accumulation of vehicles in Region a with destination in Region b at the end of period k , $a, b = A, B$ [veh]	
I	Set of intersections	
L	Prediction horizon [number of control period]	18
P^i	Set of phases of intersection i , $i \in I$	
M^i	Set of streams an intersection i , $i \in I$	
$x_m^i(k)$	Calculated mean queue length of stream m at intersection i during period k , $i \in I$, $m \in M$ [veh]	
$\lambda_{Arterial\ i}$	Predefined arterial flow entering respectively measured arterial flow leaving the network at intersection $i = 0, 14$ [veh/h]	2600 (inflow)
λ_{ab}	Calculated total flow from region a into region b , $a, b = A, B$ [veh/h]	
μ_m^i	Calculated departure flow of stream m at intersection i in period k , $i \in I$, $m \in M^i$ [veh/h]	
q_m^i	Measured arrival flow of stream m at intersection i in period k , $i \in I$, $m \in M^i$ [veh/h]	
s_m^i	Maximum discharging flow of stream m at intersection i during green in period k , $i \in I$, $m \in M^i$ [veh/h]	
g_p^i	Green time ratio of phase p at intersection i for cycle C during period p , $i \in I$, $p \in P^i$	
u	Free flow speed on a link corresponding to the speed limit [m/s]	13.89(A);8.34(B)
w	Shock wave speed of vehicles [m/s]	-5.8
r	Red time of corresponding side street approach	
q_{max}	Capacity-flow of one lane [veh/h]	2200(A);1860(B)
k_{max}	Jam density of one lane [veh/m]	0.15
$g_{p,min}^i$	Minimum allowed green time ratio for phase p at intersection i , $i \in I$, $p \in P^i$	0.1
$g_{p,max}^i$	Maximum allowed green time ratio for phase p at intersection i , $i \in I$, $p \in P^i$	0.67

1 *Input Data*

2 As it is evident from the objective equation (1), the required data inputs for the controller are:
3 traffic accumulation in region A and queue lengths at entry intersections. The output are the green
4 ratios, which are then used in the computations for the next period. For calculating other values,

1 real-time simulated measurements are used. In order to obtain all the necessary data, a very dense
 2 virtual detector covering is required. Namely, detectors are placed on every entry and exit of the
 3 arterial. Approximation through extrapolation would be a possibility in case of a lack of detectors.
 4 Alternatively, different data sources or other types of detectors (e.g. microwave radar, video image
 5 detection) could serve as input. Besides that, connected vehicles as suggested by (21), GPS data
 6 from mobile phones (26), navigation devices (27), or a combination of sources, could provide the
 7 required input data too.

8 RESULTS

9 In the following, simulation results are interpreted and discussed. As previously explained, effi-
 10 ciency of the controller is first evaluated for the no DBL case. The objective is to validate that the
 11 framework developed for large-scale traffic flow models can be adapted to micro-simulation and is
 12 a consistent for a detailed description of traffic dynamics. This approach is complementary to the
 13 work of (21). Then, the controller can be safely applied to bus operations. Especially, we study the
 14 opportunity of replacing a DBL by a gating strategy while maintaining high commercial speed for
 15 the bus lines. To this end, four different scenarios can be identified, see 2. Obviously, comparison
 16 of Sc.2 with Sc.3 is the most insightful approach to examine if gating is an alternative of DBL.
 17 In addition, Sc.4 will be used to evaluate the performance of the controller as mentioned earlier.
 18 Finally, Sc.1 is set aside because it is probably too extreme and would not make sense to apply it
 19 in the real world.

TABLE 2 Scenarios

		Dedicated Bus lane	
		Yes	No
Controller	Yes	1	2
	No	3	4

20 Efficiency of the Multi-Scale control scheme

21 Primarily, the consequences of applying the presented controller to the urban arterial are illustrated
 22 by comparing Sc2 with Sc4. Traffic in the arterial is expected to move faster thanks to the control
 23 scheme which optimizes the signal plans.

24 *Traffic Conditions*

25 Here we define two variables as performance indicators: vehicle accumulation, mean speed, and
 26 mean density in the arterial. These parameters are common as traffic performance indicators,
 27 especially against the background of the MFD concept (28). Previous studies, such as (16) or (21),
 28 introduced the same measures. The results are described in Figure 2 below. Left column holds for
 29 the traffic performance in case Sc4 in contrast to case Sc2 on the right side.

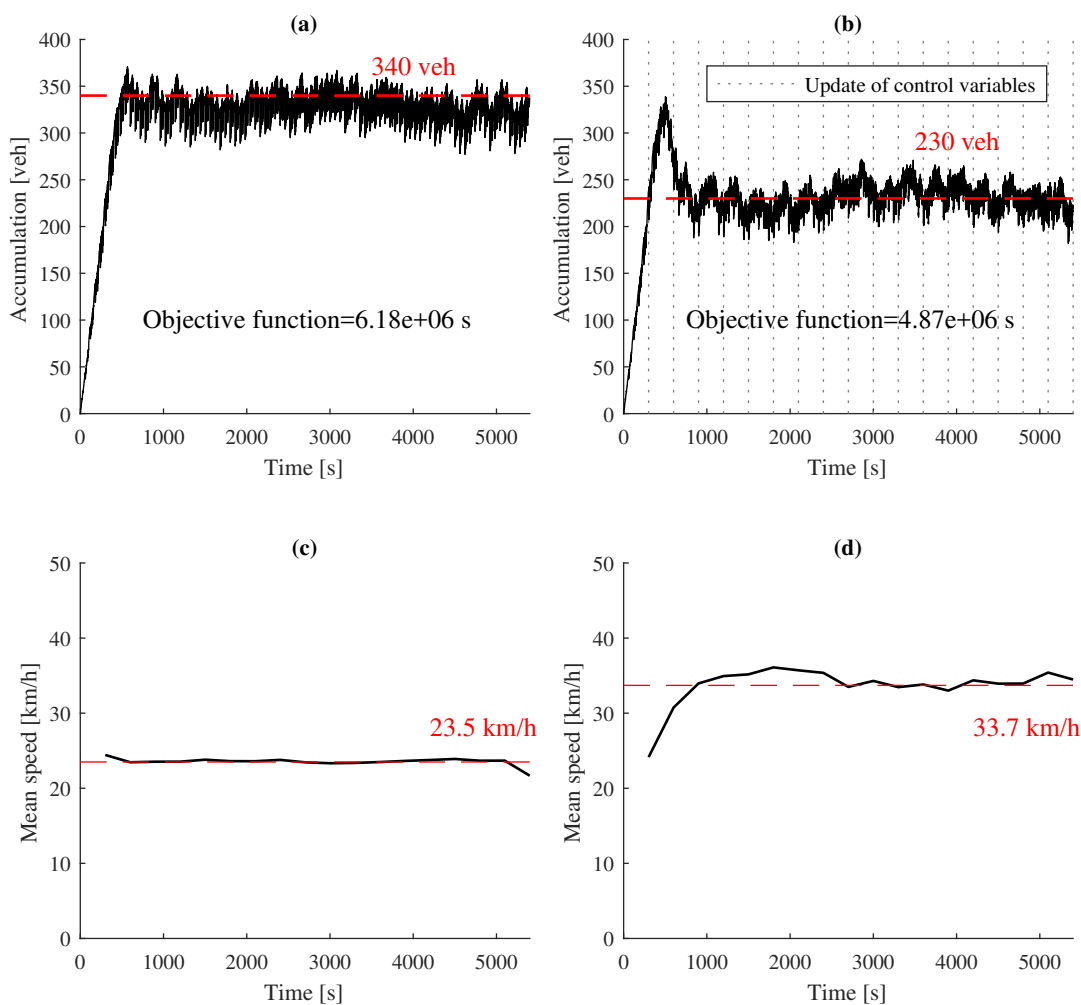


FIGURE 2 Traffic performance in the urban arterial illustrated by vehicle accumulation (a,b), mean speed (c,d) and mean density (e,f). Left column: Case A. Right column: Case B

1 As expected under constant demand, the vehicle accumulation in the arterial stabilizes over
 2 time, although on a lower level when control scheme is implemented, see Figure 2a and b. This
 3 is because the controller extends green phases for the arterial if there is no or a small queue at the
 4 related entry. In average there are approximately 100 vehicles less in the arterial for case B. The
 5 accumulation curve in Figure 2b peaks at the beginning as new signal plans are allocated to the
 6 traffic lights for the first time after five minutes. Notice that the objective function is lower for
 7 *Sc2* than *Sc4*. As a consequence the level drops again, when the controller starts operating. The
 8 controller interventions are illustrated in Figure 2b through the vertical, dashed lines. Accordingly
 9 to less waiting time respectively less accumulation in the controlled arterial, vehicles can drive on
 10 a significantly higher mean speed, see Figure 2c and d. The difference between case *Sc2* to case
 11 *Sc4* is 10 km/h in average. Overall, it can be stated, that the proposed controller improves traffic
 12 performance, represented by the three parameters named above, strongly and constant over the

1 whole simulated period. Differences become even clearer when demand in the arterial is increased
2 up to 3000 veh/h and higher. But in this case, heavy congestion is caused in the arterial for *Sc4*
3 and results become less illustrative for the comparisons. Another indicator for improved traffic
4 performance is the total arterial output, both at the main arterial exit and at side street junctions.
5 During the whole simulation run, nearly 300 vehicles more passing the arterial are measured in
6 *Sc2* compared to case *Sc4*.

7 **Application for bus operation**

8 In urban arteries or boulevards, DBLs are common in many cities as they promise various advan-
9 tages as described for example by (29). Primarily bus times and service reliability are improved
10 through DBLs. As shown in the previous section, the proposed controller enhances traffic perfor-
11 mance in the arterial considerably, as a consequence traffic moves faster. From this point of view,
12 one can argue, that the DBL becomes superfluous as their original purpose is now redundant. In
13 addition, the DBL have the disadvantage of reducing the arterial capacity devoted to general traf-
14 fic (8). When searching at optimizing the transportation system at a global level, such a strategy
15 can be counter productive (10) Therefore, the potential DBL replacement by the perimeter control
16 scheme is tested in the following by comparing the travel time of buses in the arterial for three
17 cases and in the described simulation environment.

18 As previously explained, we now focus on the comparison of *Sc2* with *Sc3* where a DBL
19 is deployed on the most right lane. Buses run with a frequency of 5 minutes through the arterial.
20 There are five stations and dwell times are fixed to ten seconds for each station. These conditions
21 hold for all three cases. Note that dynamic dwell times, i.e. dwell times that depend on the effective
22 time headways between two successive buses, have been tested. Such an approach leads to similar
23 results since bus system is very regular for the different test cases. Figure 3 provides the graphical
24 results of the comparisons. The travel time of the two last buses in the simulation are neglected,
25 because simulation stops before these buses arrive to their destination.

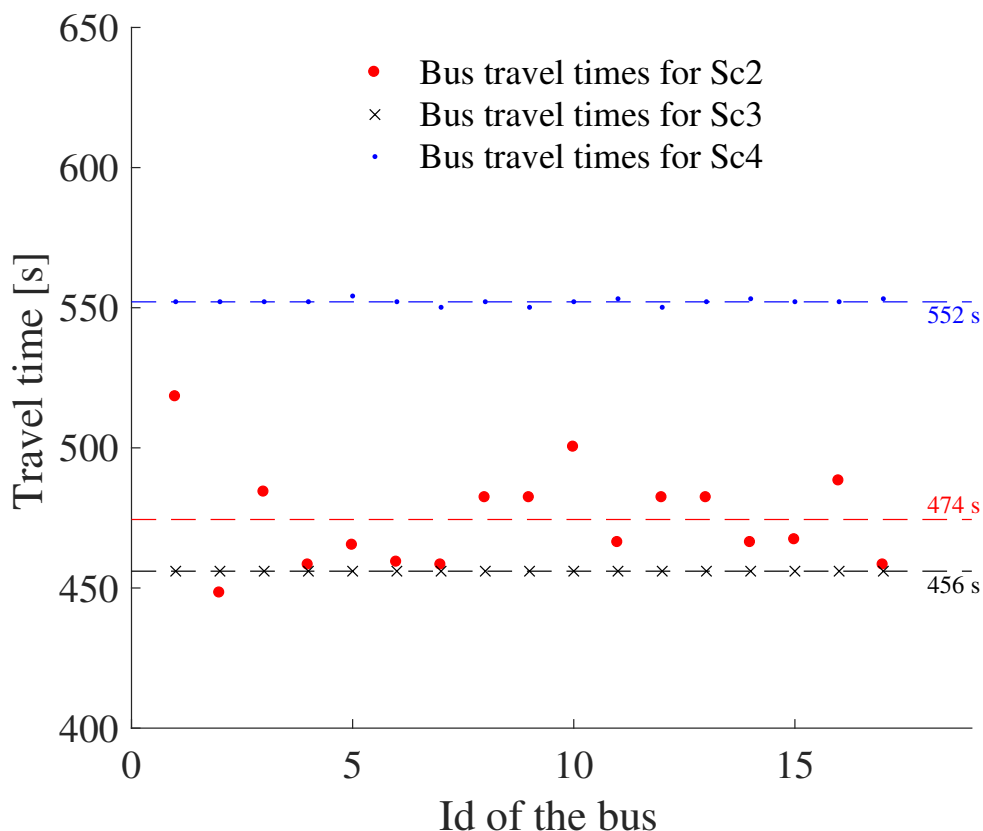


FIGURE 3 Travel time of buses through the urban arterial for scenarios *Sc2*, *Sc3* and *Sc4*. Every point corresponds to one bus trip.

1 Due to the constant dwell time and fixed traffic signal timing , the variations in travel time
 2 are relatively small for cases *Sc4* and *Sc3*. For *Sc2*, on the other hand, shows more variations,
 3 because traffic signal timing changes from one bus trip to the following (30). However, varia-
 4 tions remain very limited. On the whole, buses pass significantly faster through the arterial when
 5 perimeter control is in operation in contrast to the reference case *Sc4*. This comes as every signal
 6 plan at the 14 intersections is optimized according to the current traffic situation. Thanks to the
 7 controller, almost 1.5 minute per bus can be saved in average compared to the reference scenario
 8 without any traffic management. This corresponds to a reduction in bus travel time of 15 % for the
 9 three kilometers long arterial. Surely this difference in favor of case *Sc2* will grow with increasing
 10 distances traveled. Moreover the advantages of the control scheme regarding the bus operations
 11 become even more noticeable when arterial demand is increased further. Note also, that the higher
 12 inner demand during the middle section of the simulation has no visible effect to bus travel time.

1 Even when queue length's are taken into account, the controller still ensures good traffic conditions
2 in the arterial. The option with DBL (*Sc3*) still is the most efficient option. Buses can travel even
3 faster than in *Sc2* as they doesn't suffer any queues at all. However, gains of DBL compared to
4 the controller are not significant (20 seconds or 4 % per bus), considering the throwbacks of DBL
5 described before.

6 Concerning the impact on traffic flow, *Sc2* must also be favored. With DBL in operation,
7 the assigned arterial demand in the simulation can not fully be satisfied. The number of lanes for
8 general traffic is reduced from three two two, which results in heavy congestion outside and inside
9 of the arterial. Thus, the available capacity for general traffic in *Sc3* is lower than in *Sc2*. It results
10 on spillbacks at the different intersections but also upstream of the arterial. It turns out that *Sc2*
11 and *Sc3* are too dissimilar to perform a detailed comparison of the traffic conditions.

12 However, queues lengths can anyway be analyzed for scenarion *Sc2*. Indeed, besides the
13 advantages provided by the controller in terms of traffic performance, the common perimeter con-
14 trol problem of long delay caused at the perimeter intersections is proposed to be mitigated thanks
15 to the two-level controller. Figure 4 shows the queue lengths at the arterial entries for scenario *Sc2*
16 is compared. Because it is not consistent to compare with the results of scenario *Sc3* as previously
17 explained, we propose to compare *Sc2* with *Sc4*, the situation without control. Our intuition is
18 that *Sc4* gives an underestimation of the queue length of *Sc3*. Even if no control is applied in both
19 cases, arterial is a two-lane road in *Sc3* whereas three lanes are simulated in *Sc4*. Note that the
20 mean queue length over the whole simulation period is plotted.

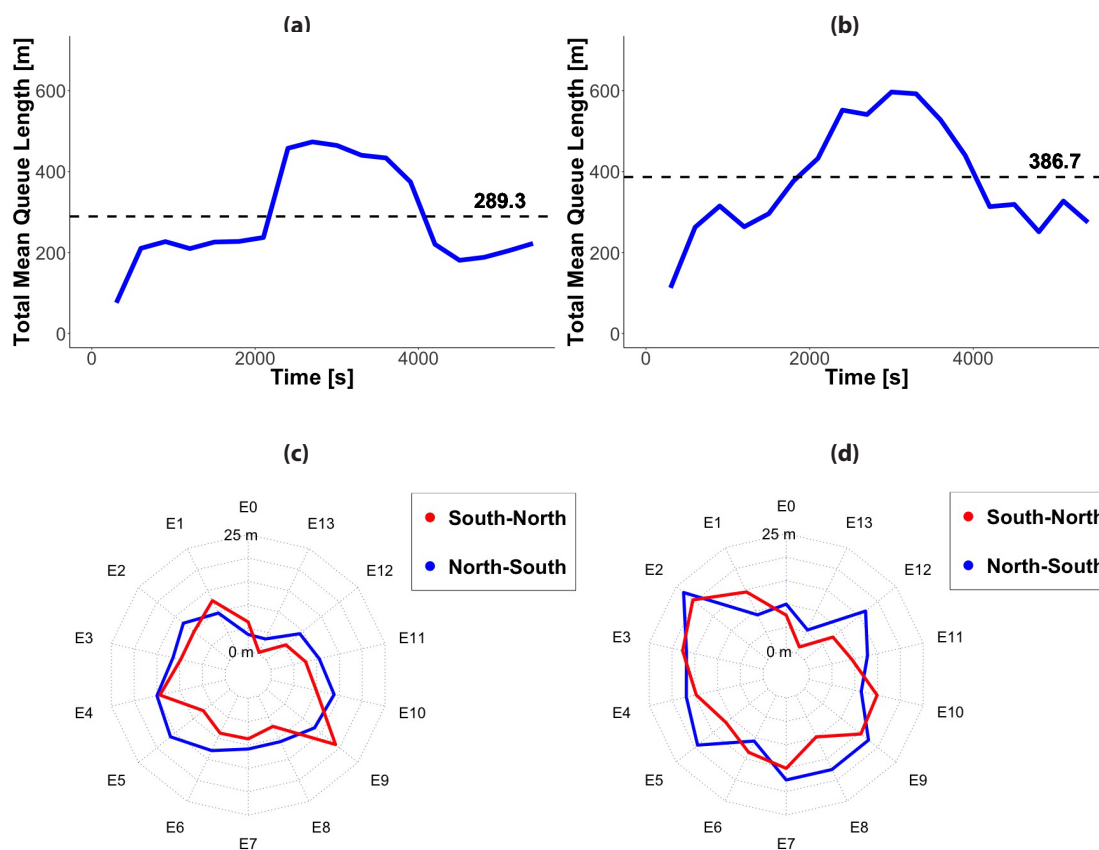


FIGURE 4 Mean queue lengths at perimeter entries cumulated over all intersections (a,b) and split up by every single intersections (c,d). Left column: $Sc4$. Right column: $Sc2$

1 Both diagrams for $Sc4$ and $Sc2$ show a comprehensible peak of queue lengths after half of
 2 the simulation time when inner demand from zone to zone in the network is increased. In average,
 3 the entry-queues are indeed longer when the controller is running, but the difference remains in
 4 reasonable limits and might be much smaller than in comparison to a bang-bang type of control
 5 algorithm, as pointed out by (21). The kiviatic (Figure 4c and d) charts highlight, that queues are
 6 quite evenly distributed among the intersections. Expect for entries 0 and 13, where queues are
 7 clearly below-average because these intersections are located right on the edge of the network.
 8 The equitable distribution is a consequence of a dynamic traffic assignment (DTA) applied in the
 9 simulation. Moreover, the graphs indicate, that queues on north-south approaches are somewhat
 10 longer in average than for the opposite direction. This is caused through the priority for vehicles
 11 coming from south over oncoming vehicles. Finally, because $Sc4$ gives only an underestimation
 12 of the queue length of $Sc3$, $Sc2$ does not have a significant effects on traffic conditions even at the
 13 intersections. These different results, i.e. decrease of bus travel times and limited effects on traffic
 14 conditions, make the replacement of DBL by perimeter control very promising.

15 DISCUSSION AND CONCLUSION

16 In this paper, we investigate, through a simulation, the potential for using perimeter control to im-
 17 prove bus system efficiency. This strategy aims at maintaining free-flow conditions in the vicinity
 18 of a major bus line, preventing buses from queuing together with cars at the intersections; thus,

1 obtaining similar benefits to those from DBL, but without drastically reducing the capacity avail-
2 able for general traffic. To prevent spill-backs outside the protected area, we resort to a multi-scale
3 perimeter controller, that is then tested with the novelty of using an urban arterial as the controlled
4 area. The control algorithm assigns the optimal green time to each of the 14 perimeter intersec-
5 tions, where side streets enter into the arterial, in order to minimize total travel costs expressed as
6 a function of vehicle accumulations. Necessary data about traffic accumulation in the arterial and
7 queue lengths at the entering links are provided through virtual detectors. Simulation results show
8 that traffic performance, as indicated by vehicle accumulation, mean speed and mean density in
9 the arterial is significantly improved with the control approach applied compared to the reference
10 case without controller.

11 Because traffic conditions remain in free-flow when activating the controller, it is suggested
12 to replace dedicated bus lanes in the arterial with the proposed control scheme. As explained
13 before, disadvantages of DBL could be eliminated thanks to this measure. The hypothesis was
14 confirmed by simulation, which shows that perimeter control is a possible alternative to DBL.
15 As a matter of fact, bus travel times with the perimeter control algorithm, are almost as fast as
16 bus travel times when using a DBL. At the same time, the available capacity for general traffic is
17 higher, and this leads to reductions in overall delays. As a result, perimeter control leads to better
18 traffic conditions both inside and outside of the protected area. Overcoming the various drawbacks
19 of DBL into consideration, perimeter control can therefore be a promising alternative as a traffic
20 management strategy in urban arterials.

21 To further pursue this research direction, the controller can still be modified and extended.
22 For instance, the two objective criteria for the proposed controller are weighted the same in the
23 present study. The weighting could be adapted for other policy goals. Focus can be directed more
24 towards queue lengths for instance. Additionally, other data sources could be used for the measure-
25 ments, besides loop detectors. This could lead to an increase in the accuracy of the estimations, as
26 these alternative technologies become more reliable, especially for high demand situations, during
27 which loop detectors are possibly covered by vehicles and therefore, imprecise. Furthermore, the
28 introduced feedback-controller could be extended to an MPC-model, including also a prediction
29 of traffic conditions. Another additional option is to shorten the control period down to one or two
30 minutes instead of five minutes, and maybe increase the efficiency of the controller.

31 Further comparisons could be made taking transit signal priority together with DBL into
32 consideration, which probably results in additional time savings for buses traveling on DBL. As
33 well, another strategy applicable are bus lanes with intermittent priority, as they represent a dy-
34 namic solution that offer more capacity to general traffic compared to DBL. In the same vein, it
35 could be investigated if bus lanes could also been replaced when the controlled region is larger
36 and includes a city center. Finally, the fact, that the simulated environment is simplified should
37 be taken into consideration when results are interpreted. On a larger scale, the enhanced traffic
38 performance through perimeter control increases the attractiveness for motorized individual traffic
39 which results in higher demand and doesn't necessarily reduce congestion in a long term view as
40 described by (31). Altogether, the proposed perimeter control scheme is very beneficial, because
41 it improves the traffic conditions in a certain area and prevents it from exceeding demand.

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