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The Intermittent Bus Lane signals setting within an area

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Abstract

Intermittent Bus Lane (IBL) used for bus priority is a lane in which the status of a given section changes according to the presence or not of a bus in its spatial domain: when a bus is approaching such a section, the status of that lane is changed to BUS lane, and after the bus moves out of the section, it becomes a normal lane again, open to general traffic. Therefore when bus services are not so frequent, general traffic will not suffer much, and bus priority can still be obtained. This measure can be operating at a single city block, but if all related control parameters along bus lines are considered together, more time gains can be obtained. In this paper, the basic structure and operation of IBL around a single intersection are briefly introduced, then the construction of an objective function and its relationships with the related priority control parameters along one bus line and their simplifications are described. Finally the calculations of the priority control parameters when there are several connected bus lines within an area and some simulation results are discussed.

Keywords: Bus priority; Public transport; Bus lane; Traffic control

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Nomenclature

$a_{k_j,11}(j)$ the entrance of IBL on arm k_j at A_j
$a_{k_j,12}(j)$ the exit of IBL on arm k_j at A_j
A_j the jth intersection
A_{j++} a group of intersections downstream of A_j along a bus line
d_r the average distance between consecutive vehicles when the queue is about to be discharged
d_q the average space occupied by a vehicle in the queue
$D_{bj}(i)$ delays of a bus at A_j in the ith cycle under $\underline{X}_j(i)$
$D_{b,j,k_j}(i)$ delays of a bus at A_j in the ith cycle under $\underline{X}_{jp}(i)$
$D_j(i)$ the delays of vehicles facing intersection A_j in the ith cycle
k_j a bus coming to A_j from its west, south, east or north is represented respectively by $k_j = 1, 2, 3$ or 4.
$l_{k_j}(j)$ the length of arm k_j at A_j
$r_j(i)$ split in the ith cycle at A_j
$t_{b,j,k_j}(i)$ the moment a bus coming to $a_{k_j,11}(j)$ of A_j after its ith cycle starts
$t_{\mathrm{IBL},j,k_j}(i)$ the moment of IBL signals turned on at arm k_j of A_j
T cycle length
$\mathrm{Tra}(j)$ a combination of the achievement to bus and influences to other traffic flow only at A_j
$\mathrm{Trb}(j)$ a combination of the achievement to bus and influences to other traffic flow only at A_{j++}
$\mathrm{Tri}(j_0, J_0)$ total traveling of a bus from A_{j_0} to A_{J_0}
$\mathrm{Trt}(j, J_0)$ the objective function
v_b desired bus speed
W_{b,j,k_j} total delays of a bus at A_j
$W(j_0, J_0)$ a weighed combination of the achievement to bus and influences to other traffic flow along the bus line from A_{j_0} to A_{J_0}
$\underline{X}_j(i)$ the general traffic control parameters at A_j in the ith cycle
$\underline{X}_{jp}(i)$ the priority control parameters at A_j in the ith cycle
α_1 the weight coefficient for the importance of intersections
α_b the weight coefficient for the importance of a bus
β_m the weight coefficient for the importance of lines
$\varphi_{0,j}(i)$ offset in the ith cycle at A_j
$\Delta\underline{X}_j(i)$ a shift from $\underline{X}_j(i)$

1. Introduction

In recent years interest has grown for granting priority to bus with signals control, by the developments of technologies in computer, communication, sensors, and Automatic Vehicle Locating (AVL) (Bell, 1992; Hounsell and Cheney, 1999; Balke et al., 2000; Mirchandani et al., 2001). But in cases with heavier traffic, even if dynamic locations of buses are exactly known, when no dedicated bus lanes are provided, buses may still be involved in the general traffic flow, sometimes having to suffer heavy time losses. In practice, because it is not always possible to easily find free space for the bus lanes, especially in city centres, permanent dedication of one lane in the cases with lower frequency of bus services is very inefficient.

This has led to the new concept of Intermittent Bus Lane (IBL), introduced by Viegas (1996). This is a lane in which the status of a given section changes according to the presence or not of a bus in its spatial domain: when a bus is approaching such a section, the status of that lane is changed to BUS lane, and after the bus moves out of the section, it becomes a normal lane again, open to general traffic. This will ensure that the privileged lane status is active only for the time strictly needed for the bus to run through it with less delays, and the normal traffic does not suffer much because this is applied to streets with low frequency of bus services. The change of lane status is marked by the change of condition (on/off) of a series of longitudinal lights along the line separating that lane from the next lane. Such a solution should be much more efficient than that simply managing green times as buses approach intersections, as there are very frequent cases of significant congestion all along the length of streets and avenues, irrespective of the distance from the intersections.

The structure of IBL system and its basic principle, the movements of vehicles and buses on the IBL, the integration of IBL on an existing Urban Traffic Control (UTC) system, the influences of IBL signals to other flow, the related priority signal settings around a single intersection and its advantages with simulation have been described in the papers (Viegas and Lu, 1997, 1999, 2001).

In practical cases, a bus has to pass through several intersections on its way. Although whenever a bus comes to an intersection the related priority signals could be turned on, and its movement at this intersection can be improved, the fact that the traffic flows between intersections influence each other, recommends that the signals for more than one intersection be considered together.

In most existing UTC systems, signals at different intersections are co-ordinated to handle these influences, so that the traffic flow within an area is improved (Gartner, 1985; Shepherd, 1994). For instance in SCOOT (Robertson, 1986; Bretherton et al., 1998), the cycle times at every intersection within an area or sub-area are the same, and the offsets and splits are used to adjust the influence between intersections.

But optimisation in these systems is aimed at the general traffic flow, not at buses. Furthermore some settings like offsets are closely related to the speeds of traffic flow. Therefore under the same signal settings, buses might actually be delayed more than the average of other vehicles. In calculating the priority signals for buses, when several intersections are considered together, a big improvement can be expected.

This paper describes the application of IBL technique within an area where there are several bus lines, showing how the co-ordinated setting of IBL (longitudinal) signals and traffic control (transversal) signals at a set of intersections in an urban area can significantly improve the overall performance of traffic movements in that area. In Section 2, the basic structure and operation of IBL around a single intersection are briefly introduced. In Section 3, some relations when a bus moves along a bus line with IBL are established, then their simplifications are described in Section 4. Section 5 shows the calculations of priority signals when there are several connected bus lines within an area. Finally, an example and some conclusions are given in Section 6.

2. The basic principle and operation of IBL technique

The concept of IBL technique could be realized in several practical ways, but first it should be designed to be operating under all necessary restraints, rules and safety from the point view of traffic engineering (McShane et al., 1998). One of them is to install some kind of longitudinal light signal equipment on the pavement along the separation line between the IBL lane and its adjacent lane, the status of the IBL lane being shown through the aspect of those signals, based on the approach of buses and other traffic situations (Viegas and Lu, 1997; Ehmanns and Ludmann, 2000). Approaching buses and other vehicles will have their degrees of freedom defined by the settings of those signals, just like it happens with normal traffic signals at intersections.

In order to make the proposed IBL technique be easily accepted by both bus and vehicle drivers, and also to facilitate their management and control in practical cases, the similar structures of bus-priority facility, which have been used in Freeways, Arterial Streets or Terminals, and rules for the movements of buses and other vehicles on them can be used here. A simplified structure of an IBL based on the normal road section is shown in Fig. 1, where the rightmost lane on the input arm to intersection A_j is used as an IBL, with a geometry similar to that of a normal bus lane. Its 'entrance' and 'exit' are separately at $a_{1,11}(j)$ and $a_{1,12}(j)$. Some kind of light signals will be placed on the pavement along the dividing line between lane 11 and lane 12. The status of lane 11 will be changing according to these signals. For example, when the longitudinal lights all are flashing on, the status of lane 11 is that of a special bus lane, whose function now is the same as the normal bus lane, where only buses (and some other priority vehicles) can enter and be moving. And after the longitudinal lights all have been turned off, lane 11 is changed back to a normal one, open to all vehicles accepted on that street.

Movements of buses on a bus lane (when they are respected) always suffer little influence from other vehicles. But in dealing with the IBL, because lane 11 is in the normal lane status (open access) before the IBL signals are turned on, some "general" vehicles are moving on lane 11. If there were many vehicles in lane 11, the coming bus would suffer heavy delays, thus receiving much less priority than with a normal bus lane. The IBL scheme must be designed so that this will not happen.

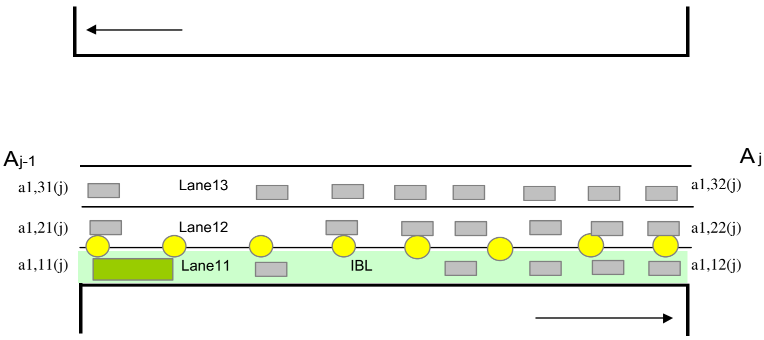

Fig. 1. A simplified structure of IBL.

The system is designed to not permit the vehicles on lane 12 to pass through the flashing separation line into lane 11. It should also not be possible for the vehicles which are moving on lane 11 to freely switch into other lanes, for safety and flow stability reasons. In order to decrease the influences by other vehicles to the bus movement on IBL, there should be few other vehicles on it, like on a normal bus-lane. Instead of from *space*, here the measure is done from *time*. In other words, the design of the system is based on giving enough ''flashing separation'' time before the arrival of the bus to a given street section, to allow an effective longitudinal (downstream) discharge of the vehicles that were driving on that lane, and restricting at the same time any additional entry of general traffic onto that section.

Now suppose the IBL signals have been turned on before the moment bus arrives at $a_{1,11}(j)$. After that, since vehicles on IBL keep moving out of the stop-line at $a_{1,12}(j)$, but no new vehicles entering into IBL, until the bus comes to $a_{1,11}(j)$, there should have already been a release of space in front of it on lane 11, thus allowing the bus to keep moving at its intended speed. In other words, for any traffic flow case, the free space in front of an approaching bus could always be obtained through adjusting the on-switching moment of the related IBL signals (supposing the traffic originally occupying the section of road ahead of $a_{1,11}(j)$ has conditions to keep flowing, thus releasing the space where it was). Normally the heavier the traffic flow is; the earlier the IBL signals should be turned on. For a lighter flow, they are turned on later, and under very light flow conditions, IBL signals do not even need to be switched on.

Because the flashing IBL signals have direct influences to the traffic flow besides them on lane 11 and lane 12, but the bus movement is influenced only by the traffic flow in front of it and no longer by the flow behind it, the IBL signals after the position of the moving bus are not necessarily kept on. Here they will be designed to be automatically turned off following the moving bus, or the IBL signals in front of and behind the bus are separately kept on and off. After the bus moves out of lane 11, all flashing lights are off, therefore all space on lane 11 is changed back to be in normal lane status again.

Although some of the effects of concentration of general traffic in $n-1$ lanes still occur after the system is switched back to normal traffic control mode, those effects actually are distributed also to the other arms of the intersection, based on the traffic conditions detected on each of them, and then soon disappear in less than one or two cycles (Viegas and Lu, 1997, 1999, 2001).

Normally, IBL would not be operating independently, but integrated with a conventional UTC system, as UTC systems have already been installed in many cities (Shepherd, 1994). The general structure of the integrated system is similar as a conventional UTC system, but with two additional interfaces (Viegas and Lu, 2001). One is connected to a kind of AVL system, and the other is for driving IBL signals. Although simple loop detectors are not sufficient for bus location, some AVL technologies, like GPS system, have been successfully used for bus location with accuracy around 5 m (Smith et al., 1994; Hill, 2001). The IBL lights would probably consist of LED arrays installed in a small box inserted in the pavement. LED arrays are extremely visible and reliable, because they have multiple small lights working in parallel. At every box, there is an element to keep these small lights on or off, based on commands issued by a local controller. Installation costs should not be too high, as the LED system is installed in some of Madrid's main arteries, just to highlight the division line of a regular (permanent) bus lane. The control parameters of the integrated system are going to be the moments of the related IBL signals being turned on and the signal settings at intersections.

3. The movement of a bus along a bus line

In this section, the question in interdependencies of signal settings at intersections along a bus line is treated. Within a road network, suppose there are J intersections, A_j ($j = 1, 2, \ldots, J$) and every one has a typical structure with four two-way streets being connected. Along every input arm where a bus line may pass through, there are at least two lanes, therefore one of them could be used as an IBL if it is needed as in Fig. 1. Traffic signals are operating at every intersection, which normally are represented with cycle T, split r, and offset φ (TRB, 1994). The control parameters in the ith cycle ($i = 1, 2, 3, \ldots$) at intersection A_j then can be described by $\underline{X}_j(i) = (T_j(i), r_j(i), \varphi_{0,j}(i))$. In practice, the optimal control parameters, $\underline{X}_j^*(i)$, can be continuously adjusted on optimising an objective function, which might have many forms, like delays, stop, capacity etc. (Shepherd, 1994). Because the proposed system is going to improve the trips of buses, the delays are chosen as the objective function. In other words, after the signal settings $\underline{X}_j^*(i)$ are applied, the vehicles facing intersection A_j in the ith cycle will have minimised delays, $D_j(i)$, which could be easily obtained (McShane et al., 1998). Similarly, for all J intersections, the control parameters are jointly chosen with $\underline{X}(i) = (\underline{X}_1(i), \underline{X}_2(i), \ldots, \underline{X}_J(i))$, and a general objective function with $D(i)$, which is a kind of combination of all $D_j(i)$, or $D(i) = F(D_1(i), D_2(i), \ldots, D_J(i))$. The optimal control parameters at all J intersections in the ith cycle, $\underline{X}^*(i)$, then are obtained through optimising $D(i)$. For simplicity (Diakaki et al., 2000; Chang and Lin, 2000; Papageorgiou, 1995), the cycle time at every intersection is assumed as fixed, i.e. all intersection have the same cycle time T, or $T_j(i) = T$ for all i and j.

First suppose there is only one bus line passing through some intersections within the area from A_{j_0} to A_{J_0}, and now a bus is moving towards intersection A_j from $a_{k_j,11}(j)$ at the moment $t_{b,j,k_j}(i)$ after its ith cycle starts or at $t = iT + \varphi_{0,j}(i) + t_{b,j,k_j}(i)$ ($0 \leqslant t_{b,j,k_j}(i) < T$), where $k_j = 1, 2, 3$ or 4 represents respectively that the bus is coming to A_j from its west, south, east or north. Under the control parameters, $\underline{X}_j^*(i)$, this bus will be delayed for $D_{bj}(i)$ at A_j in the ith cycle (Viegas and Lu, 2001).

For the same bus, now suppose the bus priority with IBL technique is used, i.e. IBL signals on the related arm k_j are going to be applied at $t = iT + \varphi_{0,j}(i) + t_{b,j,k_j}(i) + t_{\mathrm{IBL},j,k_j}(i)$, where $t_{\mathrm{IBL},j,k_j}(i) < 0$ or $t_{\mathrm{IBL},j,k_j}(i) > 0$ means that IBL signals are turned on before or after the moment the bus comes to $a_{k_j,11}(j)$, and the signals at intersection A_j are also shifted from the point $\underline{X}_j^*(i)$ to $\underline{X}_j^*(i) - \Delta\underline{X}_j(i)$ (Viegas and Lu, 2001). Since the original $\underline{X}_j^*(i)$ have been calculated from an UTC system, only $\Delta\underline{X}_j(i)$ and $t_{\mathrm{IBL},j,k_j}(i)$ are needed to be adjusted for bus priority. The actual bus priority control parameters at A_j then are defined with $\underline{X}_{pj}(i) = (\Delta\underline{X}_j(i), t_{\mathrm{IBL},j,k_j}(i))$. Now under $\underline{X}_j^*(i)$ and $\underline{X}_{pj}(i)$, the delays of the same bus at A_j in the ith cycle are only $D_{b,j,k_j}(i)$. Because the delays of bus are also influenced by its coming moment, $D_{b,j,k_j}(i)$ then can be described as a function of $\underline{X}_j^*(i)$, $\underline{X}_{pj}(i)$ and $t_{b,j,k_j}(i)$, say $D_{b,j,k_j}(i) = F_{j,k_j,0}(t_{b,j,k_j}(i), \underline{X}_j^*(i), \underline{X}_{pj}(i))$ (Viegas and Lu, 2001).

The bus then should spend $l_{k_j}(j)/v_b + D_{b,j,k_j}(i)$ to pass through arm k_j and intersection A_j after the priority signals are applied, where $l_{k_j}(j)$ is the length of arm k_j and v_b is the expected speed of the bus moving along it. If $t_{b,j,k_j}(i) + l_{k_j}(j)/v_b + D_{b,j,k_j}(i) < T$, the bus can pass through intersection A_j within the ith cycle, then it will no longer be affected by the signals at A_j after the ith cycle, or $D_{b,j,k_j}(i+1) = 0$. Otherwise it is still at A_j and will be influenced by the signals of the $(i+1)$th cycle. Similar as in the ith cycle case, its delays in the $(i+1)$th cycle will be a function of $\underline{X}_j^*(i+1)$, $\underline{X}_{pj}(i+1)$ and $t_{b,j,k_j}(i+1)$, where $t_{b,j,k_j}(i+1)$ is influenced by $t_{b,j,k_j}(i)$, $\underline{X}_j^*(i)$ and $\underline{X}_{pj}(i)$.

In UTC systems, if two intersections are too far apart, normally their signals cannot (and should not) be co-ordinated (Robertson, 1986). Here it is supposed that the bus can move from one intersection to the next one within two cycles. In case of two intersections being very far away, the movements of a bus passing through these two intersections are also supposed to be not directly influencing each other and the priority control parameters at two such intersections are calculated independently. The total delays of bus at A_j, W_{b,j,k_j}, then are chosen with $W_{b,j,k_j} = D_{b,j,k_j}(i) + D_{b,j,k_j}(i+1)$.

Along this bus line, say the intersection after A_j is A_{j+1}. The bus will come to $a_{k_{j+1},11}(j+1)$ of intersection A_{j+1} at the moment $t = iT + \varphi_{0,j}(i) + t_{b,j,k_j}(i) + l_{k_j}(j)/v_b + W_{b,j,k_j}$. Because the ith cycle at A_{j+1} starts at $t = iT + \varphi_{0,j+1}(i)$, in which $\varphi_{0,j+1}(i)$ might be different from $\varphi_{0,j}(i)$, this moment is assumed to be located within its (i_{j+1})th cycle, or at $t = (i_{j+1}) \cdot T + \varphi_{0,j+1}(i_{j+1}) + t_{b,j+1,k_{j+1}}(i_{j+1})$ $(0 < t_{b,j+1,k_{j+1}}(i_{j+1}) < T)$, in which i_{j+1} and $t_{b,j+1,k_{j+1}}$ (i_{j+1}) can be obtained directly through,

$$i_{j+1} \cdot T \leqslant i \cdot T + \varphi_{0,j}(i) + t_{b,j,k_j}(i) + l_{k_j}(j)/v_b + W_{b,j,k_j} - \varphi_{0,j+1}(i_{j+1}) < (i_{j+1} + 1) \cdot T \tag{1}$$

$$t_{b,j+1,k_{j+1}}(i_{j+1}) = i \cdot T + \varphi_{0,j}(i) + t_{b,j,k_j}(i) + l_{k_j}(j)/v_b + W_{b,j,k_j} - \varphi_{0,j+1}(i_{j+1}) - i_{j+1} \cdot T \tag{2}$$

From (1), it is known that i_{j+1} is related to $l_{k_j}(j)$ and W_{b,j,k_j}. If the block is short and the bus suffers little delay at A_j, it might be $i_{j+1} = i$, i.e. the bus moves to the next intersection even within the same cycle, otherwise, i_{j+1} might be more than one cycle later. The total delays of the bus at intersection A_{j+1}, $W_{b,j+1,k_{j+1}}$, will be calculated similarly as for A_j.

Along the bus line suppose the bus now is at intersection A_{j_0}. Its total travelling from A_{j_0} to A_{J_0}, $\mathrm{Tri}(j_0, J_0)$, can be directly obtained through,

$$\mathrm{Tri}(j_0, J_0) = \sum_{j=j_0}^{J_0} (l_{k_j}(j)/v_b + W_{b,j,k_j}(j)) \tag{3}$$

If $\mathrm{Tri}(j_0, J_0)$ is chosen as the objective function, and all control parameters, $\underline{X}_j^*, \underline{X}_{pj}$ $(j \geqslant j_0)$, are obtained through $\mathrm{Min\,Tri}(j_0, J_0)$, the bus will be travelling in less time along the line from A_{j_0} to A_{J_0}. But in the meantime, the general traffic flow might also be strongly influenced (delayed), which is also important in practice. In order to get more advantage for the bus while reducing those negative influences on general traffic, the objective function used here is chosen as

$$W(j_0, J_0) = \alpha_b \cdot \mathrm{Tri}(j_0, J_0) + W_d(j_0, J_0) \tag{4}$$

In which $W_d(j_0, J_0)$ is the total penalty (sum of time losses) to other traffic at the intersections from A_{j_0} to A_{J_0} after the related priority signals have been applied (Viegas and Lu, 2001). And α_b is the weight coefficient for the importance of a bus compared to the other vehicles in general traffic. The bigger α_b is taken; the more important the bus is. If $\alpha_b = 0$, no consideration for the bus even exists. After a bigger α_b is used, the buses can get more advantages, but also bigger delays will be imposed on general traffic. α_b then is adjusted on practical situations to get different levels of bus priority, and also different influences to other traffic flow. The "natural" rule would be to take α_b equal to the ratio between the average numbers of people being transported in a bus and in a vehicle (mostly private cars) in the general traffic.

The optimal bus priority control parameters, $\underline{X}_{pj}$, $(j \geqslant j_0)$ could be obtained directly through $\mathrm{Min}(\alpha_b \cdot \mathrm{Tri}(j_0, J_0) + W_d(j_0, J_0))$. It now has become a typical mathematical programming problem. If all their relationships are known, the control parameters at all intersections A_j ($j \geqslant j_0$) after (i_{j_0})th cycle can be computed, cycle by cycle and intersection by intersection, until the bus passes through the last intersection, A_{J_0}, on the bus line.

Although traffic flows could be estimated or predicted, in practical situations as they are affected by many factors, the traffic situations several cycles later or/and several intersections away cannot be estimated so accurately. And furthermore, when dealing with the individual bus, although its current location could be known by various types of sensors (Hill, 2001), it will become more difficult to accurately predict its future locations.

In the existing UTC systems, normally the control parameters for near cycles are adjusted continuously, based on the new information (messages from sensors) to keep its objective function at optimal values, but the signal settings for several cycles later are not yet known. Since the integrated system is based on an existing UTC system, if $\underline{X}^*$ have not been obtained, $\underline{X}_p$ cannot be known too.

So that, from both the calculations and the messages that could be used, it will be very difficult to directly obtain all control parameters in (4), and the process should be simplified. The following chapter addresses the simplification procedure.

4. The simplification of the controls

In order to simplify some results in last section, those non-important factors should be neglected. First, according to the principle of IBL technique, the system should be designed to allow the bus to be moving at a speed close to v_b thus $\sum_{j=j_0}^{J_0} l_{k_j}(j)/v_b$ would not be directly related to $\underline{X}_j^*$ and $\underline{X}_{pj}$, therefore these values are going to be not included into the objective function.

For all intersections along the line from A_j to A_{J_0}, they could always be divided into two parts, one containing only A_j, and the other one containing the following intersections A_{j+1}, $A_{j+2}, \ldots, A_{J_0}$, which here will be represented as A_{j++}. Based on this division, $\mathrm{Tri}(j, J_0)$ and $W_d(j, J_0)$ in $W(j, J_0)$ all can be further divided into two parts too, or $\mathrm{Tri}(j, J_0) = \mathrm{Tri}(j) + \mathrm{Trn}(j)$ and $W_d(j, J_0) = W_d(j) + W_{dn}(j)$, in which $\mathrm{Tri}(j)$ and $W_d(j)$ are only related to the signal settings at A_j, $\underline{X}_{pj}$, $\mathrm{Trn}(j)$ and $W_{dn}(j)$ are directly related to signals at A_{j++}, say $\underline{X}_{pj++}$, and indirectly to $\underline{X}_{pj}$ as the moment when the bus is coming to A_{j+1} was influenced by $\underline{X}_{pj}$. Because when a bus comes to A_{j+1} after A_j, $\underline{X}_{p(j+1)}$ among $\underline{X}_{pj++}$ is going to be adjusted again, to the bus still standing at intersection A_j, it will actually suffer less influences from $\underline{X}_{p(j+1)}$ at A_{j+1} than from the choice of $\underline{X}_{pj}$ at A_j. Similarly, the influences become weaker and weaker from A_{j+2}, $A_{j+3}, \ldots$ In other words, in $W(j, J_0)$, $\mathrm{Tri}(j)$ and $W_d(j)$ should be clearly more important than $\mathrm{Trn}(j)$ and $W_{dn}(j)$. After these factors are combined, based on $W(j, J_0)$ in (4), the general objective function is constructed with $\mathrm{Trt}(j, J_0)$,

$$\mathrm{Trt}(j, J_0) = \alpha_b \cdot \mathrm{Tri}(j) + W_d(j) + \alpha_1 \cdot (\alpha_b \cdot \mathrm{Trn}(j) + W_{dn}(j)) = \mathrm{Tra}(j) + \mathrm{Trb}(j) \tag{5}$$

in which $\mathrm{Tra}(j) = \alpha_b \cdot \mathrm{Tri}(j) + W_d(j)$ and $\mathrm{Trb}(j) = \alpha_1 \cdot (\alpha_b \cdot \mathrm{Trn}(j) + W_{dn}(j))$, and here $\alpha_1 < 1$ is chosen, for $\mathrm{Trn}(j)$ and $W_{dn}(j)$ are not so important. $\mathrm{Tra}(j)$ is a combination of the time gains of the bus and delays to general traffic only at A_j, whereas $\mathrm{Trb}(j)$ covers the same combination for the following intersections.

Now when a bus is coming towards $a_{k_j,11}(j)$ of intersection A_j along its trip from A_{j_0} to A_{J_0}, the optimal priority control parameters, $\underline{X}_p^*$, can be directly obtained through $\mathrm{Min\,Trt}(j, J_0)$. If $\frac{\partial \mathrm{Trt}(j,J_0)}{\partial \underline{X}_p}$ exists, the results of Min Trt(j, J_0) could be directly calculated through $\frac{\partial \mathrm{Trt}(j,J_0)}{\partial \underline{X}_p} = 0$ (Anderson and Moore, 1990). Since $\underline{X}_{pj}$ and $\underline{X}_{pj++}$ are the priority control parameters at different intersections, $\underline{X}_p$ could be further divided into two independent parts, $\underline{X}_p = (\underline{X}_{pj}, \underline{X}_{pj++})$, $\frac{\partial \mathrm{Trt}(j,J_0)}{\partial \underline{X}_p} = 0$ then also has two parts,

$$\begin{cases} \dfrac{\partial \mathrm{Trt}(j,J_0)}{\partial \underline{X}_{pj}} = \dfrac{\partial \mathrm{Tra}(j)}{\partial \underline{X}_{pj}} + \dfrac{\partial \mathrm{Trb}(j)}{\partial \underline{X}_{pj}} = 0 \\ \\ \dfrac{\partial \mathrm{Trt}(j,J_0)}{\partial \underline{X}_{pj++}} = \dfrac{\partial \mathrm{Tra}(j)}{\partial \underline{X}_{pj++}} + \dfrac{\partial \mathrm{Trb}(j)}{\partial \underline{X}_{pj++}} = 0 \end{cases} \tag{6}$$

in which $\frac{\partial \mathrm{Tra}(j)}{\partial \underline{X}_{pj++}} \equiv 0$ as Tra(j) is only related to $\underline{X}_{pj}$ at A_j, but not to $\underline{X}_{pj++}$ at other intersections.

Suppose now the optimal results obtained directly from (6) are in $\underline{X}_{pj}^{(1)}$ and $\underline{X}_{pj++}^{(1)}$. In the practical control process, since the signals are going to be adjusted cycle by cycle and also intersection by intersection, when the bus is moving towards intersection A_{j+1} after A_j, the control parameter at A_{j+1}, $\underline{X}_{p(j+1)}$, which belongs to $\underline{X}_{pj++}$, will be adjusted again. According to the new detected or estimated traffic message, which of course are more accurate than their previous estimates at the moment when the bus was at A_j, the new control parameters at A_{j+1} and $A_{(j+1)++}$, say $\underline{X}_{p(j+1)}^{(2)}$ and $\underline{X}_{p(j+1)++}^{(2)}$, can be obtained through $\frac{\partial \mathrm{Trt}(j+1,J0)}{\partial \underline{X}_p} = 0$, or $\underline{X}_{pj++}$ are changed from $\underline{X}_{pj++}^{(1)}$ to $\underline{X}_{pj++}^{(2)}$ on the new message.

Furthermore, when $\underline{X}_{pj++}^{(2)}$ are given to $\underline{X}_{pj++}$, instead of with $\underline{X}_{pj++}^{(1)}$, the new results obtained from $\frac{\partial \mathrm{Tra}(j)}{\partial \underline{X}pj} + \frac{\partial \mathrm{Trb}(j)}{\partial \underline{X}pj} = 0$ are changed to $\underline{X}_{pj}^{(2)}$. In other words, if the priority signal settings at intersection A_j are applied with $\underline{X}_{pj}^{(2)}$, it could be controlled better than in $\underline{X}_{pj}^{(1)}$, since $\underline{X}_{pj}^{(2)}$ and $\underline{X}_{pj++}^{(2)}$ are results obtained from situations closer to the real ones. But at this moment, as the bus has already passed through A_j and the signal settings in $\underline{X}_{pj}^{(1)}$ were actually applied at A_j, it is impossible to change the signal settings at A_j from $\underline{X}_{pj}^{(1)}$ to $\underline{X}_{pj}^{(2)}$. It means that even $\underline{X}_{pj}^{(1)}$ and $\underline{X}_{pj++}^{(1)}$ are the results, which are calculated very accurately from (6), but because of some un-predictable factors at other intersections, A_{j++}, the obtained $\underline{X}_{pj}^{(1)}$ still might not be the best one for the controls at the intersections downstream along the line.

As it has been explained above, normally the farther two intersections are apart; the weaker their relations are. To the bus being at A_j, the traffic situations at A_{j++} have less influences than at A_j to the bus movement, which means that some intersections which are too far away from A_j along the line can be discarded from A_{j++}, say only one, two or three intersections will be used for A_{j++}, where lower weights are used for the intersections farther away.

According to the practical traffic situations and the locations of bus line, theoretically, there could be many different ways to simplify Trb(j). Here the terminal cases are used for their simplifications. So called terminal cases are the cases which may be most probably happening at A_{j++}, and their relationships with $\underline{X}_{pj++}$ are described by some static representations, instead of being described dynamically in detail. After a terminal case for Trb(j) is given, the process to calculate the optimal control parameters at A_j, $\underline{X}^*_{pj}$, is similar to the case of individual intersections. In some UTC systems (Shepherd, 1994), like in TRANSYT, as the control parameters are chosen according to different time periods, the signal settings at A_{j++} could be known in advance. In other systems, like SCOOT, although the detected traffic messages are used to determine the signal settings, which are varying cycle by cycle, but normally in order to decrease the influences, the signals between two adjacent cycles are not adjusted too much, so the estimated signal settings at every intersection within a few cycles still could not be very deviated from the real ones.

Although when IBL signals are applied earlier, more advantages can be obtained to the bus movement, IBL signals should not be applied too early if we don't want to penalise general traffic too much. For most cases, it is found that the obtained t_{IBL} are distributed around $t_{\text{IBL}} = 0$, (Viegas and Lu, 2001). So that one of special settings used in the terminal case then could be chosen with $t_{\text{IBL}}(j_{++}) = 0$, i.e. the IBL signals at A_{j++} are assumed to be turned on separately at the moments whenever the bus arrives at their entrances. As in a practical case, after the bus comes to intersection A_{j_1} ($j_1 > j$), $t_{\text{IBL}}(j_1)$ is going to be determined again, the real operating $t_{\text{IBL}}(j_1)$ might be different from $t_{\text{IBL}}(j_1) = 0$, but in average, it is closer to the point t_{IBL} $(j_1) = 0$ than to any other real $t_{\text{IBL}}(j_1)$. Therefore in adjusting the IBL signals from this point, the produced influence will be smaller than from other points.

After one of the terminal cases is given, $\underline{X}_{pj++}$ will become constants instead of variables, therefore in (6), it should be in $\frac{\partial \text{Trb}(j)}{\partial \underline{X}_{pj++}} \equiv 0$, and Trb($j$) then is changed to be a function only related to $\underline{X}_{pj}$. The optimal $\underline{X}^*_{pj}$ can be directly obtained from $\frac{\partial \text{Tra}(j)}{\partial \underline{X}_{pj}} + \frac{\partial \text{Trb}(j)}{\partial \underline{X}_{pj}} = 0$.

As it is shown in (6), from the other side, if $\underline{X}_{pj}$ is given with $\underline{X}_{pj} = \underline{X}^*_{pj}$, the results obtained from $\frac{\partial \text{Trb}(j)}{\partial \underline{X}_{pj++}} = 0$ are the optimal ones of $\underline{X}_{pj++}$, say in $\underline{X}^*_{pj++}$. It means that if the signals at A_j have been applied in $\underline{X}^*_{pj}$, it is better to choose $\underline{X}^*_{pj++}$ as the control parameters at the next intersections A_{j++}. But in practical cases, $\underline{X}^*_{pj++}$ might be not the same as their initial settings given in the terminal case. If it is found that there are too big differences between them, the terminal case itself should be adjusted, or $\underline{X}^*_{pj}$ will be obtained through several steps of alternative between $\underline{X}^*_{pj}$ and $\underline{X}^*_{pj++}$, by which $\underline{X}^*_{pj}$ and $\underline{X}^*_{pj++}$ could be more suitable to the practical situations.

The process of alternative calculations between $\underline{X}_{pj}$ and $\underline{X}_{pj++}$ can be briefly represented as that $\underline{X}^{(1)}_{pj++}$ are first assumed to be given to $\underline{X}_{pj++}$ in the terminal case, under which the optimal values of $\underline{X}_{pj}$ are obtained through $\frac{\partial \text{Tra}(j)}{\partial \underline{X}_{pj}} + \frac{\partial \text{Trb}(j)}{\partial \underline{X}_{pj}} = 0$, say in $\underline{X}^{(1)}_{pj}$. Now after $\underline{X}_{pj}$ is given with $\underline{X}_{pj} = \underline{X}^{(1)}_{pj}$, a new set of $\underline{X}_{pj++}$ are obtained by $\frac{\partial \text{Trb}(j)}{\partial \underline{X}_{pj++}} = 0$, say in $\underline{X}^{(2)}_{pj++}$. If $\underline{X}^{(1)}_{pj++}$ and $\underline{X}^{(2)}_{pj++}$ are similar, it means that the signal settings at A_{j++}, which might be applied, are close to the pre-assumed ones, then $\underline{X}^{(1)}_{pj}$ could be used as $\underline{X}^*_{pj}$. Otherwise, the obtained results at A_{j++} are shifted from their pre-assumptions. If the difference is too big, $\underline{X}^{(1)}_{pj++}$ should be adjusted to the $\underline{X}^{(2)}_{pj++}$. Such as $\underline{X}^{(1)}_{pj++} + \alpha^{(1)} \cdot (\underline{X}^{(2)}_{pj++} - \underline{X}^{(1)}_{pj++})$ ($\alpha^{(1)} < 1$) could be chosen as the new $\underline{X}^{(1)}_{pj++}$, by which the next new $\underline{X}^{(1)}_{pj}$ and $\underline{X}^{(2)}_{pj++}$ are computed as in the previous step. The process is going to be repeated several times, until $\underline{X}^{(2)}_{pj++}$ are more or less close to their pre-assumptions.

5. Several bus lines in an area

In practice, within a same area there might be more than one bus line. If two lines are connected somewhere, the movements of buses on different lines may influence each other, so the related IBL signals along different lines should be determined together.

Normally a real bus line always crosses many intersections from its starting to the ending points, and at any given moment, more buses will be moving along it. In most cases, two adjacent buses along the same line and in the same direction are many intersections away, so we can supposed their movements do not influence each other. But for the case with more bus lines, if there is a common intersection located in the downstream paths of buses on different lines, their movements will influence each other. Because the locations of all buses are changing with time, their downstream intersections are also changing. When there are more connected lines, it may become difficult to quickly find which buses on different lines influence each other.

In order to make the problem easy, here we first divide every real bus line with the same number but with opposite directions into two different lines, and then every line is further divided into several short lines with only one bus in each. Every short line starts from the current location of the bus and only contains the blocks and some intersections downstream, this number of relevant downstream intersections having been calibrated based on the formulas shown in the sections above.

So at different moments, the short line dealing with one particular bus may contain different blocks and intersections. All real bus lines will be divided in this way and the lines used below in this paper are the divided short lines. Therefore the connection of any two lines can be easily determined only through whether both lines have common intersections downstream from current bus locations. Furthermore, for more lines, they could always be divided into some groups, by which any line is connected with at least another line in the same group, but never connected with lines in other groups. This means that the movement of one bus will not be influenced by signals at intersections on lines belonging to another group, therefore the priority control parameters at intersections along lines in different groups can be calculated independently. While the locations of buses are changing as they move along their lines, the groups are also continuously redefined in the same way.

Suppose there are N_b lines in a group and at the ith cycle, the bus on line m ($m = 1, 2, \ldots, N_b$) is moving towards intersection A_{j_m}. For every line, its travelling objective function is shown as in (5). Since in practice lines might have different levels of importance, for instance the line along the arterial may have more priority than on the side street, here the general objective function for all N_b buses at the ith cycle is chosen as

$$\mathrm{Trt} = \sum_{m=1}^{N_b} \beta_m \cdot (\mathrm{Tra}(j_m) + \mathrm{Trb}(j_m)) \tag{7}$$

in which β_m are weight coefficients. Normally, $\beta_m = 1$, but if $\beta_m > 1$, line m is more important.

First suppose $N_b = 2$ and $\beta_1 = \beta_2 = 1$, i.e. there are only two connected lines and they are of the same importance, and along every line four downstream intersections are chosen, or along line m_1, there are intersections A_{j11}, A_{j12}, A_{j13}, A_{j14}, and along line m_2, with intersections A_{j21}, A_{j22}, A_{j23}, A_{j24}, where bus 1 and bus 2 are separately moving towards A_{j11} and A_{j21} in the current cycle.

Similarly to the case of one line, here $\underline{X}_p$ is represented by $\underline{X}_p = (\underline{X}_{pj11}, \underline{X}_{pj21}, \underline{X}_{pj11++}, \underline{X}_{pj21++})$. Although there are different connections of two lines and also different locations of bus 1 and bus 2 on the lines, they could be divided into several typical cases.

The first one is that both bus 1 and bus 2 are moving towards the same intersection $A_{j1\text{–}2}$ ($A_{j1\text{–}2} = A_{j11} = A_{j21}$) in the current cycle from different directions, then after $A_{j1\text{–}2}$, those two buses are moving towards different intersections. According to the construction of $\underline{X}_{pj}$, $\underline{X}_{pj11}$ and $\underline{X}_{pj21}$ will both be related to the signals at intersection $A_{j1\text{–}2}$, so $\underline{X}_{pj11}$ and $\underline{X}_{pj21}$ are not independent. Here a new variable is chosen with $\underline{X}_{pj1\text{–}2} = (\Delta\underline{X}_{j1\text{–}2}, t_{\mathrm{IBL},j,k_{j1}}(i), t_{\mathrm{IBL},j,k_{j2}}(i))$. Because after $A_{j1\text{–}2}$ the two buses are moving to different intersections, $\underline{X}_{pj11++}$ and $\underline{X}_{pj21++}$ become independent. $\underline{X}_p$ then can be represented as $\underline{X}_p = (\underline{X}_{pj1\text{–}2}, \underline{X}_{pj11++}, \underline{X}_{pj21++})$. In practice, sometimes two buses might be moving along the same IBL towards $A_{j1\text{–}2}$, or/and after $A_{j1\text{–}2}$ to another common intersection. In this case, it only issues priority to the first coming bus, but by following it, the second bus actually benefits too. Then two t_{IBL} in $\underline{X}_{pj1\text{–}2}$, or in $\underline{X}_{pj11++}$ and $\underline{X}_{pj21++}$ are reduced to choose only one, and the other calculations stay the same.

$\frac{\partial \mathrm{Trt}}{\partial \underline{X}_p}$ could be obtained separately through,

$$\frac{\partial \mathrm{Trt}}{\partial \underline{X}_{pj(1-2)}} = \frac{\partial(\mathrm{Tra}(j_{m1}) + \mathrm{Tra}(j_{m2}))}{\partial \underline{X}_{pj(1-2)}} + \frac{\partial(\mathrm{Trb}(j_{m1}) + \mathrm{Trb}(j_{m2}))}{\partial \underline{X}_{pj(1-2)}} \tag{8}$$

$$\frac{\partial \mathrm{Trt}}{\partial \underline{X}_{pj11++}} = \frac{\partial \mathrm{Trb}(j_{m1})}{\partial \underline{X}_{pj11++}} \tag{9}$$

$$\frac{\partial \mathrm{Trt}}{\partial \underline{X}_{pj21++}} = \frac{\partial \mathrm{Trb}(j_{m2})}{\partial \underline{X}_{pj21++}} \tag{10}$$

When the terminal cases for line m_1 and line m_2 are separately given, $\underline{X}^*_{pj1\text{–}2}$ can be directly obtained through (8).

The second case is that bus 1 and bus 2 are moving to different intersections A_{j11} and A_{j21} at the current cycle, or $A_{j11} \neq A_{j21}$, but several cycles later, they are both moving towards another common intersection, say $A_{j1\text{–}2} = A_{j13} = A_{j23}$ from different directions. However, $\underline{X}_{pj11++}$ and $\underline{X}_{pj21++}$ are not independent, for they all include the signals at $A_{j1\text{–}2}$. But since they appear in the terminal cases, after they are given, $\underline{X}^*_{pj11}$ and $\underline{X}^*_{pj21}$ can be obtained independently through,

$$\frac{\partial \mathrm{Trt}}{\partial \underline{X}_{pj11}} = \frac{\partial \mathrm{Tra}(j_{m1})}{\partial \underline{X}_{pj11}} + \frac{\partial \mathrm{Trb}(j_{m1})}{\partial \underline{X}_{pj11}} = 0 \tag{11}$$

$$\frac{\partial \mathrm{Trt}}{\partial \underline{X}_{pj21}} = \frac{\partial \mathrm{Tra}(j_{m2})}{\partial \underline{X}_{pj21}} + \frac{\partial \mathrm{Trb}(j_{m2})}{\partial \underline{X}_{pj21}} = 0 \tag{12}$$

Another case is that after bus 1 passes through intersection A_{j11} in the ith cycle along line m_1, it is moving towards A_{j21} in the ith cycle, and in the meantime, bus 2 is moving towards A_{j21} along line m_2 in the ith cycle too, or $A_{j21} = A_{j12} = A_{j1\text{–}2}$, but $A_{j11} \neq A_{j21} \neq A_{j22}$. And after that the two buses are moving towards different intersections. Similarly, $\underline{X}_p$ for this case can be reconstructed into four independent parts, $\underline{X}_p = (\underline{X}_{pj11}, \underline{X}_{pj1-2}, \underline{X}_{pj(1-2,1)++}, \underline{X}_{pj21++})$, in which $\underline{X}_{pj(1-2,1)++}$ are the signal settings at the intersections after A_{j1-2} along line m_1. In the meantime, $\mathrm{Trb}(j_{m1})$ is also further divided into two parts,

$$\mathrm{Trb}(j_{m1}) = \mathrm{Trb}_a(j_{m1}) + \mathrm{Trb}_b(j_{m1}) \tag{13}$$

in which $\mathrm{Trb}_a(j_{m1})$ represents the influences of bus m_1 at intersection A_{j1-2} and $\mathrm{Trb}_b(j_{m1})$ the influences at intersections after A_{j1-2} on line m_1. Therefore $\mathrm{Trb}_a\ (j_{m1})$ will be related to $\underline{X}_{pj11}$ and $\underline{X}_{pj(1-2)}$, but $\mathrm{Trb}_b(j_{m1})$ will be influenced by $\underline{X}_{pj11}$, $\underline{X}_{pj1-2}$ and $\underline{X}_{pj(1-2,1)++}$.

The objective function in (10) then becomes

$$\mathrm{Trt} = \mathrm{Tra}(j_{m1}) + \mathrm{Trb}_a(j_{m1}) + \mathrm{Trb}_b(j_{m1}) + \mathrm{Tra}(j_{m2}) + \mathrm{Trb}(j_{m2}) \tag{14}$$

$\dfrac{\partial \mathrm{Trt}}{\partial \underline{X}_p}$ in this case can be obtained through,

$$\frac{\partial \mathrm{Trt}}{\partial \underline{X}_{pj11}} = \frac{\partial \mathrm{Tra}(j_{m1})}{\partial \underline{X}_{pj11}} + \frac{\partial \mathrm{Trb}_a(j_{m1})}{\partial \underline{X}_{pj11}} + \frac{\partial \mathrm{Trb}_b(j_{m1})}{\partial \underline{X}_{pj11}} \tag{15}$$

$$\frac{\partial \mathrm{Trt}}{\partial \underline{X}_{pj1-2}} = \frac{\partial \mathrm{Trb}_a(j_{m1})}{\partial \underline{X}_{pj1-2}} + \frac{\partial \mathrm{Trb}_b(j_{m1})}{\partial \underline{X}_{pj1-2}} + \frac{\partial \mathrm{Tra}(j_{m2})}{\partial \underline{X}_{pj1-2}} + \frac{\partial \mathrm{Trb}(j_{m2})}{\partial \underline{X}_{pj1-2}} \tag{16}$$

$$\frac{\partial \mathrm{Trt}}{\partial \underline{X}_{pj(1-2,1)++}} = \frac{\partial \mathrm{Trb}_b(j_{m1})}{\partial \underline{X}_{pj(1-2,1)++}} \tag{17}$$

$$\frac{\partial \mathrm{Trt}}{\partial \underline{X}_{pj21++}} = \frac{\partial \mathrm{Trb}(j_{m2})}{\partial \underline{X}_{pj21++}} \tag{18}$$

After the terminal cases are given to $(\underline{X}_{pj(1-2,1)++}, \underline{X}_{pj21++})$, $\underline{X}^*_{pj11}$ and $\underline{X}^*_{pj1-2}$ can be obtained through (15) and (16).

Similarly for the case of $N_b > 2$, i.e. when there are more than two connected bus lines in a group, $\underline{X}_p$ is first divided into several independent parts, on which Trt in (7) is reconstructed, then after the terminal cases are given, the related optimal control parameters can be directly obtained like through (8), (11), (15) or (16).

While buses are moving along their lines within an area, according to their locations, the lines are continuously divided into different groups. The priority control parameters will be computed group by group, then to drive the related signals. The process is going to be repeated to continuously issue priority to the bus movements.

6. The application and conclusions

Let us now consider a small example as shown in Fig. 2. Suppose a bus is going to be moving on its path with fourteen intersections, from A_1 to A_{14}. The bus line will pass through A_1, A_2, A_3 and A_4 in direction W–E, then turn right at A_4 to through A_5, A_6, A_7 and A_8 in N–S, and then turn left at A_8 to pass through A_9, A_{10}, A_{11}, A_{12}, A_{13} and A_{14} in W–E again. The distances between

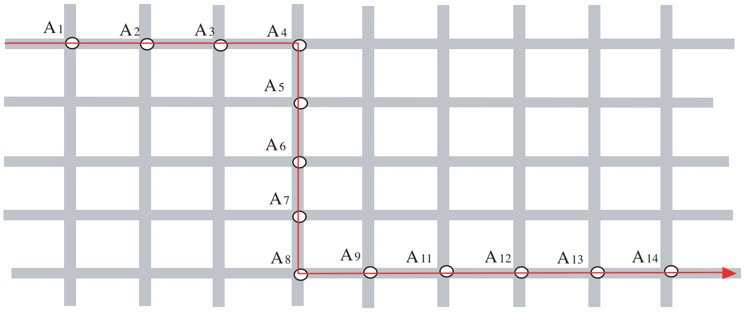

Fig. 2. A bus line passing through 14 intersections.

adjacent intersections along this path are respectively 150, 150, 100, 150, 130, 110, 120, 130, 140, 120, 130, 140, 140, 140, and 140 m. Around every intersection and on every arm, their traffic situations are also chosen similarly with, $f_c = 0.5$ veh/s, $f_{m1} = 0.20$ veh/s, $f_{m2} = 0.26$ veh/s and $f_{m3} = 0.32$ veh/s, $r_{c1} = T/3$, $r_{c2} = 2 \cdot T/3$, $v_c = 10.5$ m/s, $v_b = 8.5$ m/s, $d_q = 6$ m, $d_r = 21$ m, $T = 70$ s, $r(i) = 0.5$, in which f_c is saturation flow rate; f_{m1}, f_{m2} and f_{m3} are the average coming flow rates during three periods of one cycle, $(0, r_{c1})$, (r_{c1}, r_{c2}) and (r_{c2}, T); v_c is the average speed of traffic flow; v_b the desired bus speed; d_q the average space occupied by a vehicle in the queue and d_r the average distance between consecutive vehicles when the queue is about to be discharged (Viegas and Lu, 2001).

The priority control parameters at every intersection along the line have been calculated separately for different control strategies. The first strategy is the independent (myopic) one: when a bus comes to intersection A_j, the priority signal settings are obtained only according to the traffic situations around A_j, without considering other intersections, or $A_{j++} = 0$. In the second strategy, $A_{j++} = A_{j+1}$ has been chosen. In calculating the priority parameters at A_j, here the possible influences at intersection A_{j+1} are also included, which are obtained on the assumptions of $t_{\mathrm{IBL}}(A_{j++}) = 0$, i.e. the IBL signals at A_{j+1} are supposed to be turned at once after the bus has passed through A_j. In the third strategy, $A_{j++} = A_{j+1}$ is also chosen, but in $t_{\mathrm{IBL}}(A_{j++}) = \infty$, i.e. the delays of the bus at A_{j+1} without priority signals are used. In the fourth strategy, $t_{\mathrm{IBL}} = 0$ and $A_{j++} = 0$ are chosen, i.e. the IBL signals at any intersection will be applied at once when a bus appears there, without considering the real traffic situations.

Because after IBL signals are applied, the delays of the bus on IBL are only related to the number of vehicles ahead of it but not to their movements, and also it is not so easy to describe the influence to every individual vehicle due to IBL signals (Viegas and Lu, 2001; Leutzbach, 1988), in calculating the priority control parameters, macro-simulations have been used, in which every cycle is divided into several periods and every period has a different traffic flow condition, then the influences to a group of vehicles are calculated separately. The weight coefficients are taken as $\alpha_b = 6$, $\alpha_1 = 0.75$. While the bus is moving along the line, all related optimal priority control parameters are quickly calculated with the mountain climbing method. The obtained results with the four strategies are summarised in Table 1.

At the first line of Table 1, A_j is the number of the intersection along the bus line, and (1) means that the bus moves in W–E direction and (2), in N–S; PCP represents the priority control parameters. In the example, it chooses the change of the offset (ΔX_j) and t_{IBL}; t_b, the coming moments

Table 1
Comparison of effectiveness of different control strategies

A_j	1(1)	2(1)	3(1)	4(1)	5(2)	6(2)	7(2)	8(2)	9(1)	10(1)	11(1)	12(1)	13(1)	14(1)
PCP-1	(no, 0)	(0, 0)	(4, 0)	(no, 0)	(no, −5)	(no, −8)	(no, 0)	(0, 0)	(no, 0)	(0, 0)	(2, 0)	(−3, 0)	(no, 0)	(no, 0)
tb-1	20	38.5	52.7	−15.1	23.6	29.4	30.9	−8.2	5.5	32.9	44.2	51.8	−14.8	22.3
Db-1	15	6	4.7	33	1	0	29	11	22	9	5	0	33	14
PCP-2	(no, 0)	(1, 0)	(−4, 0)	(−2, 0)	(no, 0)	(0, 0)	(no, 0)	(no, −4)	(no, 0)	(0, 0)	(−5, 0)	(−3, 0)	(no, 0)	(no, 0)
tb-2	20	38.5	52.8	51.7	−12.5	6.9	15.5	21.5	25.2	43.6	51.3	53.3	−13.5	22.7
Db-2	15	6	1.4	0.7	14	7	4	1	13	6	0	0	33	14
PCP-3	(no, 0)	(−5, 0)	(1, 0)	(−3, 0)	(no, 0)	(0, 0)	(no, 1)	(−2, −2)	(no, 0)	(0, 0)	(−4, 0)	(−3, 0)	(no, 0)	(no, 0)
tb-3	20	38.5	49.3	52.2	−12.6	6.9	15.5	21.4	23.5	42.6	50.7	53.2	−13.7	22.7
PCP-4	(0, 0)	(0, 0)	(0, 0)	(0, 0)	(0, 0)	(0, 0)	(0, 0)	(0, 0)	(0, 0)	(0, 0)	(0, 0)	(0, 0)	(0, 0)	(0, 0)
tb-4	20	36.8	51.5	−16.4	22.6	−6.5	7.3	15.4	20.7	39.5	48.6	−15.5	21.7	38.1

Trt-1 = 421 s, Trt-2 = 352 s, Trt-3 = 352 s, Trt-4 = 429 s, Trt-5 = 507 s.

of the bus and D_b the delays of the bus at every intersection. At the bottom of the table, Trt is the total travel time of a bus along this path: "-1", "-2", "-3", "-4" and "-5", correspond to the four bus priority strategies and to the absence of priority signals.

According to the principle of IBL, IBL signals could be operating independently in each block, and also co-ordinately at several blocks along the bus line. In either way, the travelling times of a bus along the line are always improved, compared with the case without bus priority signals, as it is shown from Table 1 that Trt-1, Trt-2, Trt-3 and Trt-4 all are less than Trt-5.

From Trt-2 and Trt-3 being less than Trt-1, it is known that the priority control parameters obtained when considering more intersections together can produce bigger advantages to the bus movements than when working with one intersection at a time, but in the meantime, as in average PCP-2 and PCP-3 are similar to PCP-1 at all fourteen intersections, the general traffic flow still did not suffer greater delays in the co-ordinated strategies.

It is also found that Trt-2 and Trt-3 are similar, but in some cases, PCP-2 values are smaller than those of PCP-3, which means that the priority control parameters obtained with $t_{\mathrm{IBL}}(j_{++}) = 0$ will produce somewhat smaller delays to the general traffic flow.

In conclusion, joint consideration of IBL signals and traffic light signals at intersections leads to lower time losses in bus operation, but these gains can be significantly improved if there is an integrated control of several intersections along the bus line, with bigger advantages obtained for bus movements, with less or similar delays imposed to other traffic flow.

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