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CASE STUDY AND APPLICATION

Demonstration and evaluation of an intermittent bus lane strategy

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Abstract
The innovative concept of intermittent bus lanes may lead to an important increase of bus system performance while limiting the reduction of the capacity devoted to general traffic. The main idea is that a general traffic lane can be intermittently converted to an exclusive bus lane. Frequently studied by analytical papers, practical demonstrations of the intermittent bus lane strategy are not numerous. Especially, the results of the two previous field tests are very specific to the test sites and are hardly transposable. This paper tries to fill this gap by proposing the results and the lessons learned of a new real-field demonstration in Lyon, France. After a detailed presentation of the 350-m case study, effects of an intermittent bus lane strategy on traffic conditions are evaluated. Then, analyses of the impacts on the bus systems performance are carefully performed and also compared to more classical bus operations: a transit signal priority strategy. The results show that an intermittent bus lane can be a promising strategy especially when it is combined with transit signal priority. The median travel time of the buses is significantly reduced whereas the regularity of the line increases.

Keywords Intermittent bus lane · Traffic management · Transit signal priority · Experimentation

1 Introduction

As cities around the world grow rapidly, an accelerating demand for mobility is observed that puts a lot of pressure on the transportation networks. Because the amount of road space available is very limited, this increase yields to severe traffic congestion that strongly reduce the quality of service of transportation networks. Especially, the efficiency of public transport is heavily deteriorated by traffic jams, generating an increase of travel times and making them unpredictable.

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Local authorities and operators are, therefore, compelled to implement strategies to improve the performance of public transport networks and especially bus lines in order to increase their attractiveness. These actions can mainly operate at different levels: optimizing the bus itself (articulated bus, double-decker bus, etc.), controlling bus lines to avoid bus bunching and maintain targeted time-headways, see Berrebi et al. (2018) for a review, or changing road infrastructures (Currie and Lai 2008; Guler and Cassidy 2012; Thamizh Arasan and Vedagiri 2010; Wu and Hounsell 1998).

At the infrastructure level, transit strategies mainly fall into three categories. First, solutions related to transit signal priority (TSP) aim to provide priority to buses at signalized intersections. This solution has received a lot of attention and has been deployed all over the world (Bagherian et al. 2015; Guler and Menendez 2015). Second, dedicated (or exclusive) bus lanes (DBLs) have become widely accepted. Because of the space limitation in urban areas, the most common way of creating DBL is by converting an existing car lane because leading to a capacity reduction for private cars. Third, to overcome this limitation, researchers (Chiabaut et al. 2012; Viegas and Lu 2004; Eichler and Daganzo 2006) have proposed different variations of the dynamical bus lane concept. This system is based on the idea that a general traffic lane can be intermittently converted to an exclusive bus lane. To this end, an intermittent bus lane (IBL) seeks to restrict individual vehicles from changing into the lane ahead of the bus only when it is coming. The main theoretical advantage of IBLs is that they can be implemented on streets where the bus frequency does not necessarily justify a full-time or part-time exclusive bus lane, but where providing priority to buses is still desired. In the same time, IBLs increase the capacity devoted to private cars compared to DBL.

This paper is devoted to a field demonstration of the IBL strategy in Lyon, France. Lyon is the second-largest city in France with 1 600 000 inhabitants (25th in Europe, 266th in the world). Even if IBL strategies have been studied deeply on the analytical level, this is only the second time that IBL is actually tested in practice, after the 2006 demonstration of Lisbon, Portugal (Viegas et al. 2007). The first 6-month experiment of Lisbon reveals that IBLs can improve the efficiency of transit systems by speeding up 20% of the buses without significantly degrading the general traffic (Viegas et al. 2007). Notice that a first trial of a variation of the IBL concept was tested in Melbourne, Australia (Currie and Lai 2008). This first initiative is less efficient than the Lisbon experiment. Although the results from the trial were promising, more evidence and a wider range of practical experience with these concepts are required to justify the widespread implementation of IBL.

Nevertheless, the project of Lyon is built on the positive feedback and lessons learned of Lisbon and Melbourne. Besides, the IBL strategy is here complemented by a simultaneous deployment of TSP on the experimental site as suggested in Eichler (2006). It makes it possible to experimentally compare different bus operations. To this end, travel times of the buses are recorded during all the demonstration and are used to draw general conclusions about the IBL real-world deployment.

The paper is organized as follows. Section 2 synthesizes the most important features of the IBL experiment in Lyon and introduces the methods to analyze the

collected data. Section 3 presents the main results of the demonstration. Finally, Sect. 4 is devoted to a short conclusion.

2 Concept of IBL and demonstration project in Lyon

Introduced by Viegas and Lu (1997), the IBL strategy consists of a lane in which the status of each link changes according to the presence of a bus in the upstream vicinity. This very dynamic traffic control strategy requires a detailed analysis to select a site where IBL can lead to benefits. In previous publications (Chiabaut et al. 2012, 2014), the authors proposed a modeling framework to anticipate the potential effect of IBL and to evaluate *ex ante* a potential deployment. This methodology has been used to identify several test cases in Lyon, France. After discussions with the city and the transit agency, it has been decided that the experiment will be carried out in the Avenue Lacassagne in Lyon, France.

The chosen setting is located in the center of the city, see Fig. 1a, and is one of the major signalized arterials of the area. Figure 1b shows the design of the test case. The global site is 700 m long and presents four signalized intersections, denoted

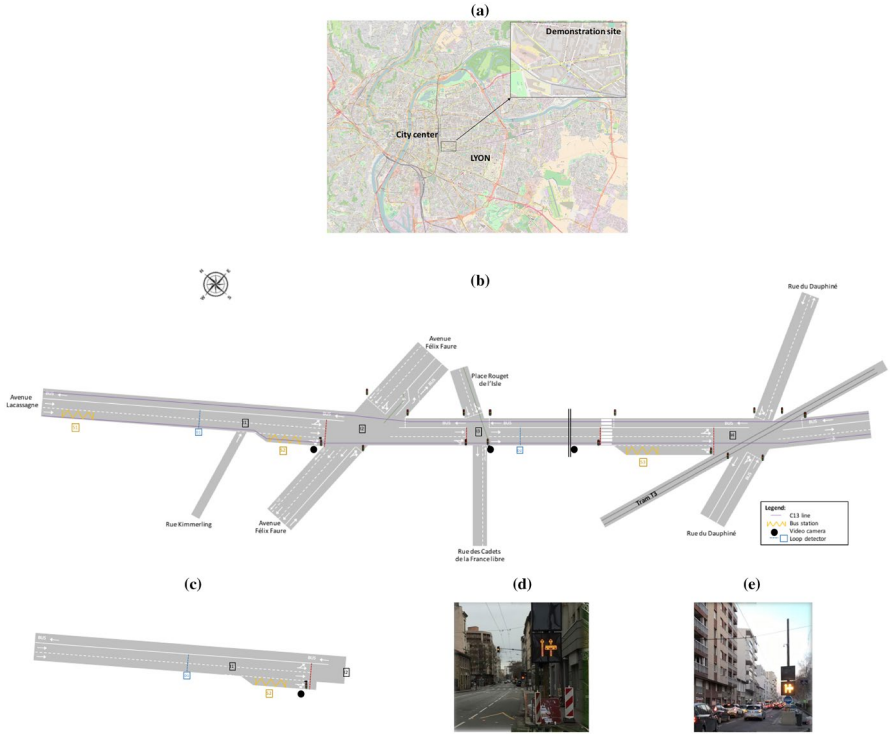

Fig. 1 **a** Localization in the city of Lyon; **b** plan of the demonstration site; **c** bus station design; **d**, **e** pictures of the equipment of the demonstration

I1, I2, I3 and I4. This is mainly a two-lanes road except in the vicinity of the bus stations S2 and S3 where a third lane is dedicated to the bus (bus turn-out stops), see Fig. 1c. The equipped section is located between intersection I2 (Avenue Félix Faure) and intersection I4 (Rue du Dauphiné), and is about 350 m long. Note that this site is shorter than those of Lisbon and Melbourne (800 m and 2100 m).

At the different intersections of the demonstration site, the entry and exit flows are very low, less than 100 veh/h. It turns out that turning movements do not have a significant impact on the traffic dynamics of the arterial. However, parking lots exist on both sides of the arterial. Many shops are located in the neighborhood of the Avenue Lacassagne. Consequently, on-street parking search may have an effect on the traffic conditions. In addition, we can observe a noticeable freight activity with numerous delivery and pick-up manoeuvers every week day. A part of these manoeuvers double-parks on the right lane of the arterial, compelling the bus to change lane.

In this arterial, three bus lines operate but only one line is equipped with the required technology to trigger the IBL. Among the large existing choice, the transit agency has selected wireless communication devices. Notice that time-headways of the line depend on the time of the day and vary from 8 min between two successive buses during peak hours and 30 min during night hours. The IBL is automatically activated all along the demonstration site when a bus of the C13 line stops or passes the station S1, see Fig. 1a. Thus, the activation length is fixed and is equal to 450 m. It is important to notice that the strategy is always activated whatever the traffic conditions are and does not require any action from the bus drivers.

At this moment, the three roadside changeable message signs implemented along the site at each of the intersections (I2, I3 and I4) and the in-pavement lights, see Fig. 1d, flash during 30 s. After that, they are continuously turned on. It indicates that drivers cannot use the right lane anymore and those already in must leave the right lane. Once the strategy has been activated, the cars are banned from the right lane along the entire arterial until the bus has passed. Notice that an information campaign was realized in advance by distributing leaflets in the mailboxes of the neighborhood. Then, when the bus arrives at the entry of the equipped section, i.e. intersection I2, the right lane has been cleared out. Note that a bus needs on average 2 min to reach intersection I2 from station S1. The activation phase can clearly be optimized by accounting for the real-time bus location. Indeed, average travel times are used to determine the time lag between the bus detection at station S1 and the IBL. It would have been better to account for the real-time traffic conditions. However, it has not been possible to do this during the experimentation.

Once the bus has passed an intersection, the associated roadside changeable message sign and in-pavement lights are turned off. Individual drivers can re-use the right lane. Consequently, IBL ends simultaneously with the trajectory of the bus, which is the liberal version of the IBL strategy (Todd et al. 2006). IBL only affects individual vehicles in front of the bus. Thus, this solution minimizes the disturbance to general traffic. Moreover, there is no right turn in the experimental site making the deployment easier. However, parking is still allowed and may disturb the buses.

The technologies that have been used for the demonstration are currently available on the market. Changeable message signs have been commonly used for decades

as well as in-pavement lights that have been implemented in many dynamic lane assignment applications. Finally, the total cost for the installation of this equipment is around 180 000€ for 350 m. This is similar to the cost of the Melbourne experience, US$500 000 in 2001 for 2100 m (Currie and Lai 2008). We do not have access to the costs of the Lisbon initiative.

The following complications due to the specifications of this location also need to be considered:

- The IBL crosses a tramway lane which has an absolute priority at the signalized intersection I4. It turns out that it may generate delays at the end of the demonstration site, that constitutes a large part of the travel time of the bus.
- There is a pedestrian crosswalk in the middle of the site that also yields to traffic disturbances.
- We also observe a lot of double-parked delivery and/or pick-up maneuvers. In addition to generating extra delays (Todd et al. 2006; Chiabaut 2015), freight vehicles stand on the right lane dedicated to buses. Consequently, buses have to change lane and to merge in the general traffic stream. This is also a source of potential delays and decreases the transit performance.
- Since no enforcement action was deployed during the demonstration, the users' acceptance and respect of the rules are not so good. By visual inspection, we observe that around 20% of the individual vehicles do not follow the instructions and use the right lane during IBL activations.

The demonstration site is also equipped with measurement devices. Two loop detectors are available and give access to flows and occupancies values (6 min aggregation). In addition, passing times of the buses at the successive stations are recorded and aggregated to provide average travel times of the buses during the different phases of the experiment. To give more details, the duration between the departure times at station S_i and the departure times at station S_{i+1} have been recorded by the transit agency. Consequently, the dwell times at stations are embedded in this measure and cannot be directly observed. Moreover, three movie cameras have been installed to record traffic for the whole period of the demonstration, see Fig. 1b. For specific needs, it makes it possible to measure other phenomena (dwell times, length of the queues, etc.) by a tedious visual inspection. Thanks to the city of Lyon, we have access to the traffic signal settings that were played during the demonstration period. These settings change with traffic conditions but also with priority rules at some intersections (especially when TSP is activated).

The IBL experiment started in January 2017 and lasted for 5 months divided into three phases corresponding to different configurations of transit operations:

- Configuration 1—C1: during phase 1 (January 9th–January 27th 2017), only the IBL strategy was activated. Note that IBL was not enabled for the buses of the two other lines.
- Configuration 2—C2: during phase 2 (March 6th–March 21st 2017), a transit signal priority (TSP) was also deployed in addition to IBL. Notice that we did not have access to the details of the TSP algorithm. However, it can be noticed

from the recorded traffic signal patterns that priority is drastically given to buses of the C13 line, cutting green phases of other movements as soon as a bus is in the upstream vicinity of an intersection. Moreover, TSP was neither enabled for buses on the opposite direction nor for buses of other lines.

- Configuration 3—C3: during period 3 (March 27th–April 14th 2017), IBL was deactivated and buses can only profit from TSP strategy.

In addition, data for a reference configuration (configuration C0 from September 27th to October 10th 2016) without any bus operation (neither IBL nor TSP) were also recorded. These observations for the general-purpose lanes (GPL) case make it possible to evaluate the effects of the IBL strategy but also to cross-compare different configurations of transit operations based on a common reference. Table 1 gives a brief description of the available data.

3 Results

Approximatively 10 weeks of data (5 days per week) were eventually available. Effects of IBL and other configurations on the transit system can be quantified by using recorded travel times of buses whereas loop detector data can be used to observe the impact on general traffic. If necessary, additional information can be obtained by a tedious visual inspection of recorded videos for specific days.

3.1 Effects on traffic conditions

Concerning the effects of the different configurations on the traffic conditions on one hand, one of the main expected benefits of IBL compared to DBL is to limit the capacity reduction for the individual cars. On the other hand, the IBL activation may generate delays for cars compared to the GPL case (Chiabaut et al. 2012). The objective is to verify if IBL provides the good trade-off between these two phenomena. When designing the demonstration, the initial idea was to investigate this particular point through flows and occupancies.

Table 1 List of available datasets

Data	Aggregation	Quantity available
Loop detector 109 (D1): flow and occupancy	6 min	10 weeks
Loop detector 342 (D2): flow and occupancy		10 weeks
Average bus travel times	30 min	37 periods per day, 10 weeks
Standard deviation of bus travel times	30 min	37 periods per day, 10 weeks
Number of buses	30 min	37 periods per day, 10 weeks
Minimal bus travel time per period of 30 min	–	37 periods per day, 10 weeks
Maximal bus travel time per period of 30 min	–	37 periods per day, 10 weeks
Traffic signal parameters	–	10 weeks
Videos	–	10 weeks

Consequently, flows have been monitored by two loop detectors managed by the city of Lyon. Figure 2a and c show the time series of flows recorded on March 8th, 2017. Note that all the days have similar trends. Besides, it can be seen that the

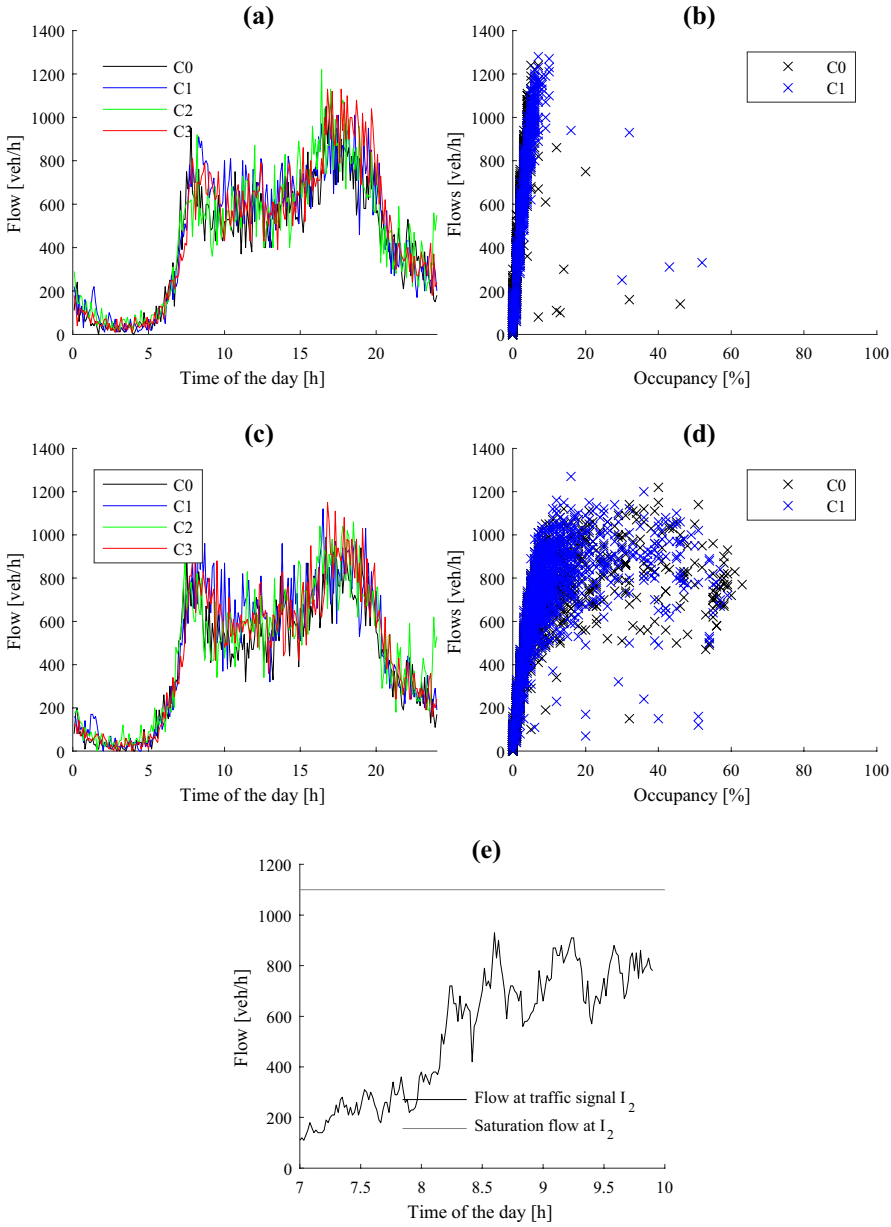

Fig. 2 Traffic conditions: **a** flows and **b** flow-occupancy curves at upstream location (D1), **c** flows and **d** flow-occupancy curves at downstream location (D2), **e** flows at the entry of the equipped section

evolution of flows during the day is very similar from one configuration to the other. Traffic is almost never congested at location D1 (non-equipped section) whereas we observe at location D2 (equipped section) some spillbacks due to traffic signals located downstream. As previously explained, tramways have an absolute priority at intersection I4. Green phases of Avenue Lacassagne can be drastically reduced. These reductions may lead to local queues that increase the travel times of buses. However, we can anyway conclude that the demonstration site is mainly in undersaturated conditions.

Moreover, Fig. 2a and c show that IBL and the other configurations have insignificant impacts on the traffic conditions. Figure 2b and d depict the flow-occupancy curves observed by each detector for configurations C0 and C1. These figures confirm that traffic conditions are similar between the different phases of the demonstration. However, this conclusion must be moderated by the fact that traffic is mainly in free-flow conditions and that we only have access to aggregated data preventing from identifying local dynamics of traffic flow.

Indeed, because the time resolution is 6 min, it is impossible to observe variations of the flow at the traffic signal scale and to analyze extra queues generated by the capacity reduction yielded by the IBL activation. To overcome this limitation, we have extracted flow values from the recorded videos. Vehicles were manually counted at the entry intersection and average flows were calculated for different time aggregation periods. Figure 2e highlights these observations. Saturation flow of the traffic signal located at the entry of the equipped section (intersection I2) has been added (gray lines). Because traffic flows remain always lower than these two boundaries, it turns out that the traffic demand is too low to observe impacts of capacity reduction due to IBL activations (Chiabaut et al. 2012).

To complete these observations, Fig. 3a and b show the distributions of the observed flows by detectors D0 and D1. It clearly appears that there is no observable difference between the four configurations. This visual conclusion is confirmed by the boxplots (Fig. 3c and d) which are strongly similar from one strategy to the other. We can now safely conclude that the IBL activation has no impact on traffic conditions on our demonstration site.

3.2 Effects on bus system conditions

For each configuration, the Lyon transit agency provided the average travel times of the C13 line by periods of 30 min (5h30–23h30). In addition to these aggregated values, standard deviations, minimal and maximal travel times, such as the number of observations for each 30-min period, are given. Notice that we do not find appropriate metrics in National Academies of Sciences, Engineering, and Medicine (2013) for IBL situations. In addition to the quality of the data (coarse measurements), these are the reasons why we used our own indicators. Figure 4a shows these rough data for the different phases of the experiment. It appears that the time evolutions of the travel times are similar between configurations. However, three different periods can be identified: night hours (dark gray), day hours (light gray), and peak hours. Notice that these periods are consistent with the observation of the traffic situations

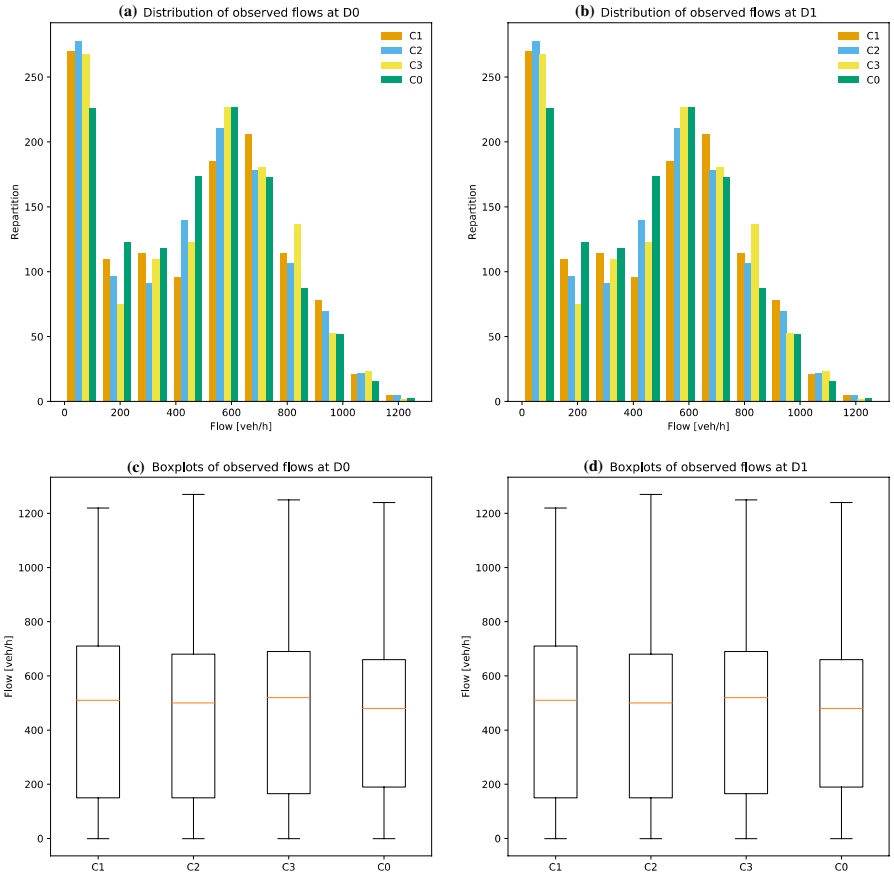

Fig. 3 Distributions of the observed flows for the different configuration at detector **a** D0 and **b** D1; boxplots of the observed flows for the different configuration at detector, **c** D0 and **d** D1

depicted in Fig. 2a and c. These periods are used in the following to quantitatively compare the different configurations. It confirms what can be expected: travel times of buses are higher during peak hours. Moreover, transit operations speed up the buses. Increases are more important when TSP is activated (configurations C2 and C3). Concerning the numbers of observations, they are very similar from one configuration to another (Fig. 4b). Finally, the gap between maximal and minimal travel times is not impacted by bus operations (Fig. 4c).

To pursue the analysis of the benefits of the different solutions, quantitative metrics are computed from these observations. The different transit configurations (C1, C2 and C3) are compared to the reference case (C0). Table 2 shows the rough percentage of the time when a configuration reduces the travel times of buses. It appears that C1 is efficient only for 43% of the day. This result is not good because IBL leads to an increase of travel times on average for the whole day (+1.1 s at the demonstration site scale). It appears that C1 clearly reduces the speed of the buses

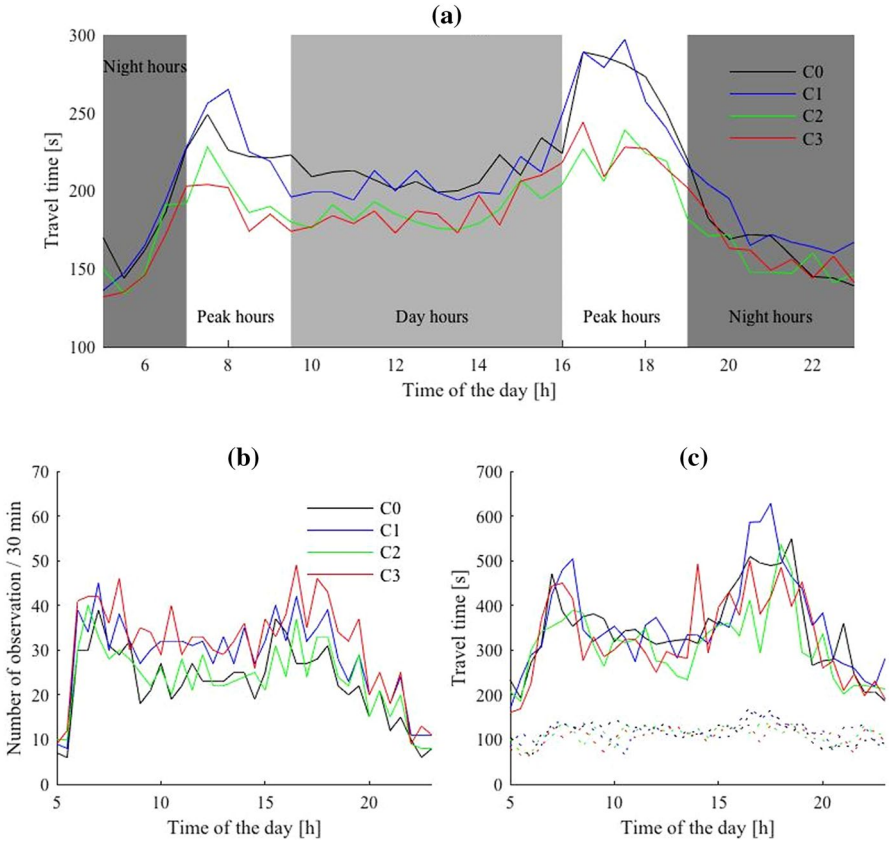

Fig. 4 Travel times of the buses for the different configurations: **a** average travel times, **b** number of observations, and **c** minimal and maximal travel times vs. time of the day

Table 2 Comparison of the different configurations with the reference situation

	C0/C1		C0/C2		C0/C3	
Total	Section 1	Section 2	Section 1	Section 2	Section 1	Section 2
	27%/+5.9 s	59%/− 4.8 s	86%/− 9.5 s	84%/− 14.5 s	86%/− 11.1 s	76%/− 12.9 s
	Total		Total		Total	
	43%/+1.1 s		89%/− 24.0 s		92%/− 24.0 s	
Night hours	10%/+5.8 s	50%/+0.6 s	60%/− 1.9 s	70%/− 6.1 s	50%/− 1.8 s	70%/− 7.0 s
	20%/+6.4 s		70%/− 8.0 s		80%/− 8.8 s	
Peak hours	21%/+10.5 s	50%/− 4.6 s	93%/− 11.3 s	93%/− 22.4 s	99%/− 15.1 s	71%/− 18.4 s
	36%/+5.9 s		93%/− 33.6 s		93%/− 33.4 s	
Day hours	46%/+1.0 s	77%/− 9.0 s	99%/− 13.4 s	85%/− 12.5 s	99%/− 13.9 s	85%/− 11.6 s
	69%/− 8.0 s		99%/− 25.8 s		99%/− 25.5 s	

Differences are expressed as the ratio of the day when a configuration outperforms the reference situations. Benefits (−) and losses (+) are expressed in seconds

because of the capacity reduction during IBL activation. Indeed, Table 2 shows that the average travel time of buses in Section 1 increases by about 5.9 s. This confirms the analytical conclusions of Chiabaut et al. (2012). However, C1 leads to travel time savings in Section 2. Unfortunately, these gains do not compensate the extra delay in Section 1. It is thus appealing to analyze thoroughly these results (see the next paragraph). Results are much better when the TSP strategy is simultaneously deployed (89% of the day and 24 s saved on average for the total site) or when only the TSP strategy is applied (92% of the day and 24 s). To isolate the effects of transit operations, the analysis of travel times in Section 1 (non-equipped) and Section 2 (equipped) is performed.

A more detailed analysis reveals that configuration C1 is more efficient for day hours rather than night or peak hours, see Table 2. It corresponds to what can be expected from previous analytical investigations (Chiabaut et al. 2014). Moreover, observed time benefit is about 4.6 s for peak hours and 9 s for day hours on the equipped section. For day hours, this benefit compensates the initial extra-delay. A similar analysis reveals that configuration C2 is efficient for peak and day hours (more than 90% of the time). Benefits can be estimated around 22.4 s and 12.5 s (respectively).

Configuration C3 leads to results comparable to those of configuration C2. It turns out that IBL activation does not lead to supplementary time savings compared to a classical TSP strategy. However, this conclusion must be moderated by the specific geometry of the demonstration site. Indeed, the good performance of the TSP can be easily explained. Station S2 is located on an extra lane, which is almost never used by general traffic (less than 90 veh/h). Consequently, this protected station, located immediately upstream of the traffic signal, associated with a TSP strategy generates a cocoon of void downstream of the bus (Eichler 2006). Because speeds of the bus and of the general traffic are similar, the bus remains in front line at each traffic signal and avoids queues. This dynamic is analogous to an IBL strategy. It may explain why we do not observe differences between configuration C2 and C3. It is also worth noticing that TSP reduces travel times by only 50% of the time for Section 1, see Table 2. Note that Sect. 1 takes advantage of the deployed TSP at the entry intersection located at the frontier of Sections 1 and 2. To explain this unexpected result, it appears that buses stop at every station during night hours, even if no passenger is waiting. After discussion with the transit authority, these dwell times are not accounted for in the settings of the TSP strategy. Consequently, buses miss the green waves during night hours. It explains why transit operations do not necessarily speed buses up during night hours.

Finally, Fig. 5 depicts the travel time distributions for the different configurations. Note that measurements, i.e. average travel times per period of 30 min, have been weighted by the number of observations per 30 min. Moreover, we focus only on the equipped section for peak hours and day hours. Figure 5a–c (respectively) show the distributions for configuration C1, C2 and C3 (respectively). Based on these distributions, median and standard deviations can be calculated for the different configurations. It turns out that the IBL strategy leads to a decrease of approximatively 10 s of travel times for the equipped section (121 s for C1 vs 131 s for C0, see Fig. 5d). As previously mentioned, the equipped section is very small for the demonstration

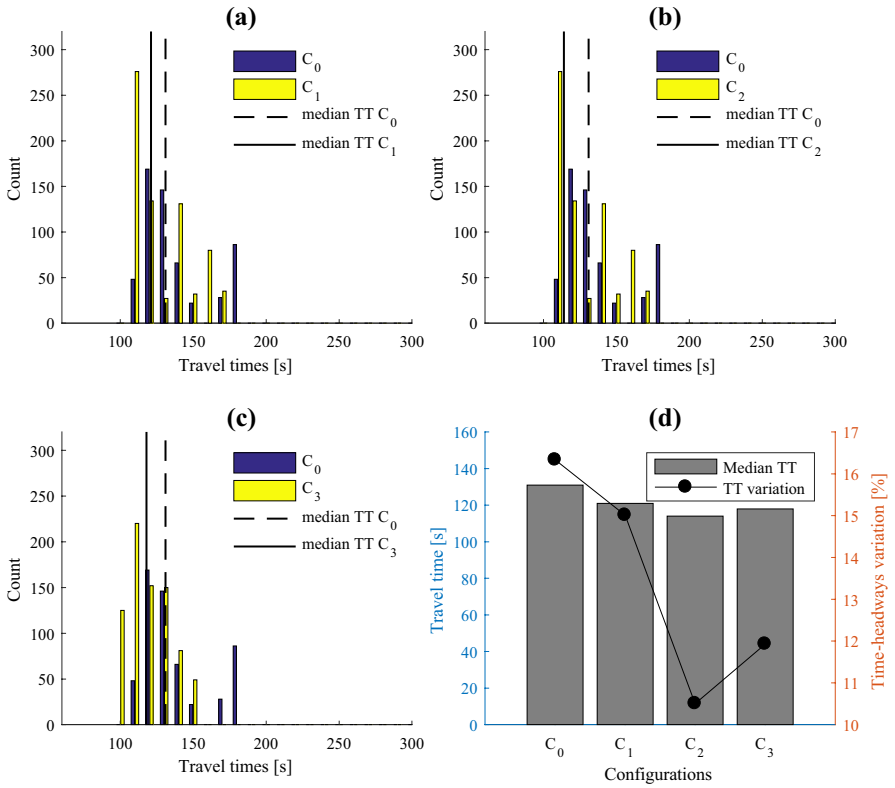

Fig. 5 Travel time distributions of the equipped section for **a** configuration C1, **b** configuration C2, **c** configuration C3 and **d** comparison of median travel time and time-headway variations

site (only 350 m and two intersections) but this result is encouraging. Indeed, once the IBL strategy is activated, we can expect a significant increase of bus system performance for longer equipped site and numerous signalized intersections. In previous studies (Chiabaut et al. 2014), the required number of equipped links is estimated at 5 to compensate for the initial extra delays due to IBL activation, i.e. lane reduction for general traffic. The experimental measurements seem to corroborate the analytical results. Note that, in terms of regularity, IBL has also a positive effect: time-headways variation is reduced from 16.3 to 15%. When activating simultaneously the TSP strategy, the decrease of median travel time is emphasized (− 17 s compared to C0, 114 s vs 131 s) such as the regularity of the bus line (10.5%). It corresponds to an average speed increase of 15%, which is similar to the benefits obtained by the Lisbon and Melbourne trials (Currie and Lai 2008). More interestingly, when only the TSP strategy is applied (configuration C3), benefits are not as important as in configuration C2. Median travel time is approximatively 118 s and time-headway variation is about 11.9%, see Fig. 5d. This result highlights the potential of the IBL strategy when TSP is applied simultaneously for peak hours. Expected benefits are even more important in the case of a longer equipped section.

4 Conclusion

This paper presents the results of a demonstration of the IBL strategy in Lyon, France. Even if this innovative solution has been deeply studied analytically, this is only the second time that IBL is tested in the field. Moreover, different configurations of bus operations are tested. Indeed, the demonstration period has been divided into four phases: GPL, IBL only, IBL and TSP applied simultaneously, and TSP only. At the same time, the traffic conditions and the bus travel times have been monitored. Recorded data can then be used to evaluate the effects of IBL on traffic and on bus system performance, and to provide feedback for further IBL deployments.

Different approaches have been followed to analyze the results. First, measurements of loop detectors show that IBL activation has no significant effect on traffic conditions. Note that traffic is almost always under saturated situations. Second, the analysis of recorded travel times reveals various interesting results. It confirms analytical investigations that IBL activation generates extra-delays upstream of the equipped section. These delays are created by the capacity reduction. At a large time-scale, the delays seem to be uncompensated by the benefits observed for the equipped section. However, a finer analysis shows that travel time measurements can be segregated into three categories: peak hours, day hours and night hours. This approach permits to observe that IBL can be efficient for peak hours and day hours. Time savings are increased when TSP is applied simultaneously. Third, distributions of travel times for the equipped section highlight that IBL can have positive effects on bus system performance. This result is promising knowing that the equipped section is narrow. Expected benefits can be much more important if IBL and TSP are deployed on a longer site.

Finally, many lessons can be learned from this demonstration. The most interesting insight is that the IBL concept, specifically when complemented by TSP, can be a promising traffic management strategy and a potential alternative to DBL. Despite the difficulties to deploy such a solution, we hope that the results of the paper will encourage and pave the way to other demonstrations in the world.

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