

# Implementation of Bus Priority with Queue Jump Lane and Pre-Signal at Urban Intersections with Mixed Traffic Operations: Lessons Learned?

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## Abstract

In mixed traffic streams, especially near the intersections, buses suffer significantly due to congestion and excessive delays compared with other modes as they operate on fixed routes. To increase the attractiveness of bus journeys by improving schedule-reliability and reducing journey times, it is necessary to give priority to buses by segregating them from the main traffic stream. However, the road space is generally constrained in the cities and dedicated bus lanes are not a feasible solution in the majority of urban centers. This paper aims to investigate the effectiveness of queue jump lanes (QJL) with and without pre-signal for non-priority traffic. The impacts on traffic and bus operations are analyzed based on implementations at two signalized approaches with distinct traffic and roadway characteristics in the Kolkata city, India. The field implementation indicated travel time savings to passengers as a whole with variations with respect to different scenarios. Impacts on travel time and vehicle discharge yielded the effective benefits of the bus priority implementation. It was also meaningful and interesting to investigate the impacts on driver behavior in terms of bus stop manoeuvres, and the social acceptability of such implementation. The changes in safety-related aspects and driver violations are some of the aspects which could not be directly investigated in an analytical or micro-simulation platform, but needed a field implementation. The experiences gained from the field implementation of bus priority with QJL are expected to encourage practitioners to apply similar treatments in other cities in emerging countries with analogous operating conditions.

Growing vehicle usage is a major influence on the urban transportation network with roads operating at or over capacity at most of the urban centers. This is leading to aggravated congestion, pollution, and safety issues (1). The key challenge in an urban context is to adapt to the growth and requirements of travel (2). Development of cities to accommodate the excessive demand in terms of private vehicle usage has proved to be an expensive and futile endeavor in the past (3, 4). Alternatively, increasing the overall attractiveness and, thereby, patronage of mass public transport services, such as bus, urban rail, tram, etc., is now well recognized as a strategy to achieve a sustainable urban transport system (4, 5).

Among the different public transport modes, buses provide one of the most flexible, space-efficient and cost-effective means with better accessibility in urban areas (2, 6, 7). However, in mixed traffic streams buses suffer significantly due to congestion and excessive delays compared with other modes as they operate on fixed routes (5, 8). In this regard, bus priority treatments enhance the perceived advantage of buses relative to single or low

occupancy vehicles in terms of improved socio-economic benefits by reduction in average passenger delays as well as congestion, and greater energy and environmental efficiency (9, 10). Therefore, bus priority measures have the potential to divert private-car users (also known as “choice riders”) to buses, leading to better utilization of road space (11, 12). Bus priority, as a strategy for bus system improvement and better utilization of road space, was introduced in the 1960s (13). It has already been successfully implemented with significant benefits in different cities worldwide (9, 14, 15). Several researches have been conducted to develop guidelines for implementation of bus priority treatments (16–18).

Intersections are one of the major causes of delay to buses operating on urban arterials (19). Hence, bus

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priority treatments at traffic signals have proved to be instrumental in improving the overall bus journey time by reductions in bus travel time delay as well as delay variability (20, 21). These, in turn, have also improved the quality and efficiency of bus operations in terms of reducing bus bunching, serving longer routes for same travel time, deployment of fewer buses without compromising with serving the demand during peak periods, etc. They also allow passengers to allocate less time for travelling to a particular destination without increasing the probability of arriving late (2, 22). Since most of the urban arterials are major transit routes, efficient operation through bus priority treatments is also likely to result in improved performances of non-priority traffic operating on bus priority phases (23). However, the effectiveness of bus priority is largely location-specific and a major part of the research has been based on the operating conditions in developed countries with lane-based, disciplined, and more or less homogeneous traffic as well as well-equipped, high performance buses. There are, however, added complexities associated with emerging countries such as India due to prevailing roadway, traffic, and control conditions. Considering the heterogeneous traffic mix and traffic congestion issues in urban Indian intersections, it is necessary to segregate the buses from the main traffic stream in order to improve the bus journey time.

Additional road space is a necessary requirement for the right-of-way allocation to buses. In this regard, dedicated bus lane corridors have proved to be beneficial in different operating conditions, such as, in Canada, Japan, China, Vietnam (24–27), etc. Bus lanes have also been implemented successfully for selected corridors in a few Indian cities. However, the road space in many Indian cities is limited and a significant portion of the roads have high vehicular demand (28). In such situations, another alternative to providing exclusive right-of-way access to buses is to implement Queue Jump Lanes (QJL) for segregating the buses from the main traffic stream near the intersections (29). Additionally, in order to reduce the conflicts of the bus with the turning traffic along the same approach, a bus advance area along with pre-signals for the non-priority traffic may also be provided where adequate road space is available. However, the effectiveness of such facilities for bus priority in the present context has not yet been adequately investigated. Only a few studies have been reported in literature, which are highly case-specific and based on traffic micro-simulation evaluation (30, 31). The majority of the works related to bus QJL in other traffic environments have also been based on analytical and simulation modeling (32–34). Due to the heterogeneity in traffic mix, absence of lane discipline, and the disorderly nature of traffic, many external factors may influence the effectiveness of

a bus priority treatment when implemented in the field. Social acceptance and change in driver attitude are some aspects which can not be modeled in an analytical or simulation framework. Therefore, real-life implications of bus QJL based on implementation in mixed traffic environments is yet to be explored.

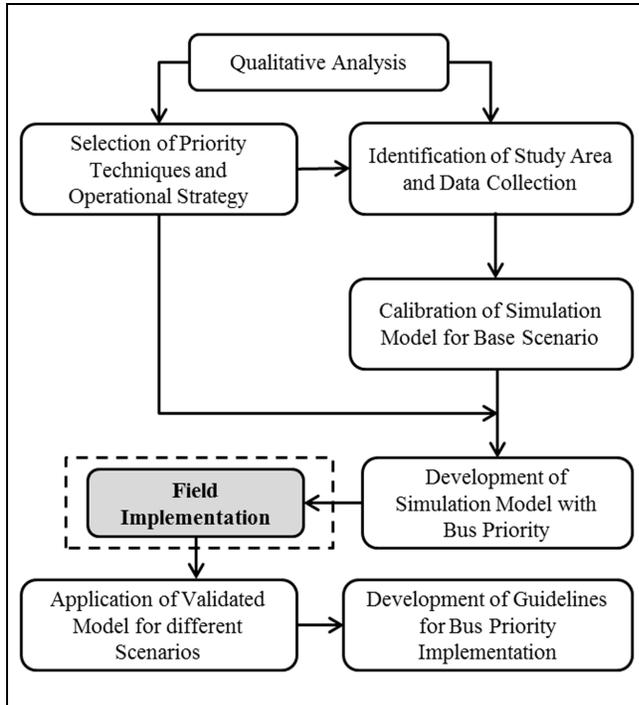
This paper aims to reflect the experiences and the impact on traffic and bus operations due to implementation of bus QJL with pre-signal for non-priority traffic on two signalized approaches with distinct traffic and roadway characteristics in the Kolkata city, India. The experiment was carried out in each of the study approaches over a period of three consecutive weekdays: first, for the base scenario; then bus priority using only QJL; and finally, bus priority using QJL and pre-signal for non-priority vehicles. The implementation of bus priority is necessary to satisfy five-fold objectives: (a) validate the results obtained from an analytical or traffic micro-simulation model; (b) check for complexities unforeseen in the simulation framework; (c) understand the operational constraints of the selected bus priority treatment; (d) understand the social acceptability of the selected bus priority treatment; (e) make some fine-tuning to the simulation model with bus priority based on the experiences from field implementation.

The paper is structured in the following sections. A brief research background in the context of implementation of QJL is presented in the next section, followed by an overview of the implementation strategy for the two selected signalized approaches. Experiences gained and findings related to the impact on bus and overall traffic operations are then discussed in the next sections. The paper finally concludes with some major findings and the future implications of the work.

## Research Background

This paper is a part of a holistic research on the selection of suitable bus priority treatments and their implications in the context of signalized intersections with mixed traffic operations in urban India. Although this paper is focussed on the implementation of a bus priority treatment, the different stages of the work (shown in Figure 1) which led to the selection and implementation of bus priority by using QJL and pre-signal are discussed briefly in the present context.

A significant number of research works have been carried out and different types of bus priority treatments have been proposed to be effective in different transportation scenarios. Therefore, the first stage of the work involved a critical review based on a qualitative analysis of all the different bus priority treatments, giving due consideration to the different traffic characteristics in emerging countries. Some treatments were identified and



**Figure 1.** Flowchart of overall research methodology.

selected which may be effective in such scenarios, and they were considered for further evaluation using traffic micro-simulation and/or field implementation. This was achieved by performing a General Morphological Analysis (35) which helped to identify potential bus priority treatments in lieu of the different road, traffic and control conditions in emerging countries, on the basis of a Morphological Box, also known as Zwicky's Box (36).

Several typical signalized intersection approaches which are representative for urban mixed traffic operation and control were identified in the next stage, and all relevant data were collected related to road geometry, traffic characteristics, and signal operations.

The traffic, roadway, and control data were then utilized to develop and calibrate a traffic micro-simulation model giving due consideration to different vehicle categories, such as car, bus, motorized two-wheelers (M2Ws), and three-wheelers (M3Ws) (or autorickshaws, also known as tuktuks). Three types of buses that are predominant in the city, viz., mini bus (MINIB), ordinary private bus (OPB) and low floor bus (LFB), have also been modeled with individual bus-specific characteristics. A genetic algorithm-based calibration technique was adopted to optimize different model parameters considering vehicle-type specific travel-time distributions as the performance measure (37).

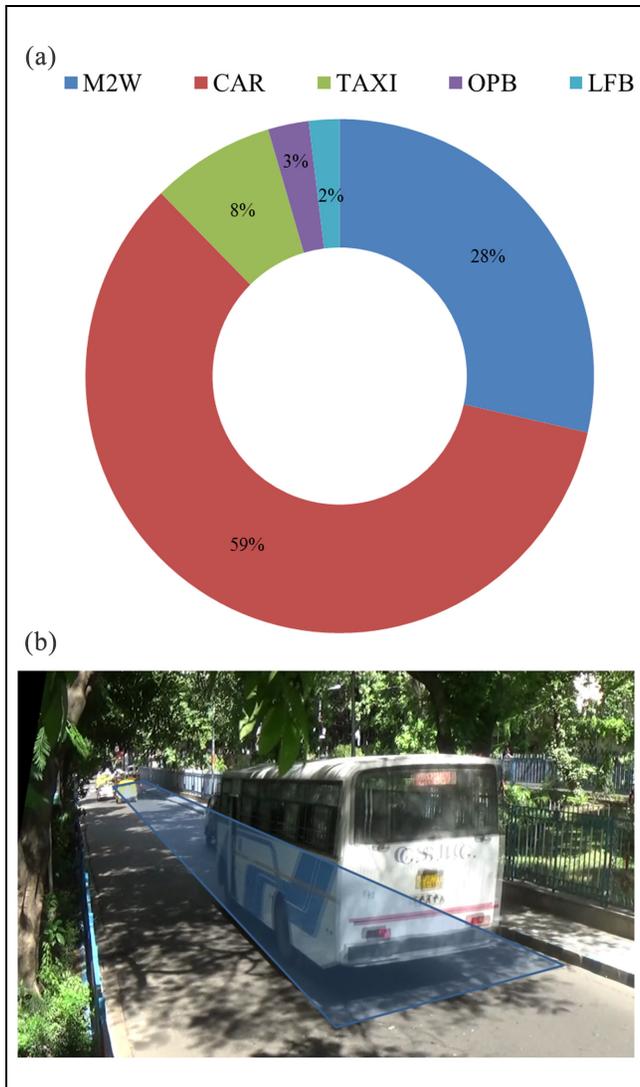
The calibrated model was then modified to incorporate the bus priority measures that were selected based on the qualitative analysis. Different scenarios were

simulated, and bus priority with QJL with or without pre-signal for non-priority vehicles was found to be beneficial under mixed traffic operating conditions.

Traffic micro-simulation tools are often unable to capture some realistic complex scenarios in the field, especially in the case of mixed traffic operations. Moreover, social acceptance and violations are other aspects which can not be modelled in a micro-simulation tool. Therefore, the next stage was to implement the selected bus priority treatment with QJL to satisfy the five-fold objectives as mentioned in the previous section, and to document the experiences gained from such field implementations. Hence, representative intersection approaches were selected for field implementation, and all relevant data was extracted from the field using videography and manual data extraction techniques. The experiences from field implementation and micro-simulation will be helpful in suggesting some guiding rules and constraints for implementation of bus priority in the present context of mixed traffic operations. This paper primarily focuses on the implementation of QJL as a bus priority treatment, and relevant experiences and findings are presented in the following sections.

## QJL Implementation

Two representative signalized intersection approaches were selected for QJL implementation and evaluation. The approaches have different geometric properties, and the traffic operations are also different in terms of traffic composition and turning movements. The experiment was carried out in several phases over a span of three days for each intersection approach. On the first day, the traffic was allowed to operate as per the present conditions. Bus priority was then provided only by QJL on the second day while, on the third day, a pre-signal was provided for the non-priority traffic lane along with the QJL. The majority of the buses in the city operate on fixed routes. Therefore, prior to the implementation of QJL, the operators of the buses plying on the specific routes covering the study locations were informed about the experiment and briefed about their roles in using the QJL at these locations. The general public in the city were also notified of this experiment at the selected locations through the aid of several regional television, electronic, and print media over a short period before carrying out the experiment. Kolkata Traffic Police, the local traffic law enforcement authority, also participated in the media campaign to educate road users about the principles of operation of QJL and pre-signals. They further extended the infrastructural support necessary for the field implementation, viz., lane segregation, signage, lane markings, and installation of pre-signals. Traffic police personnel were also present at the study locations

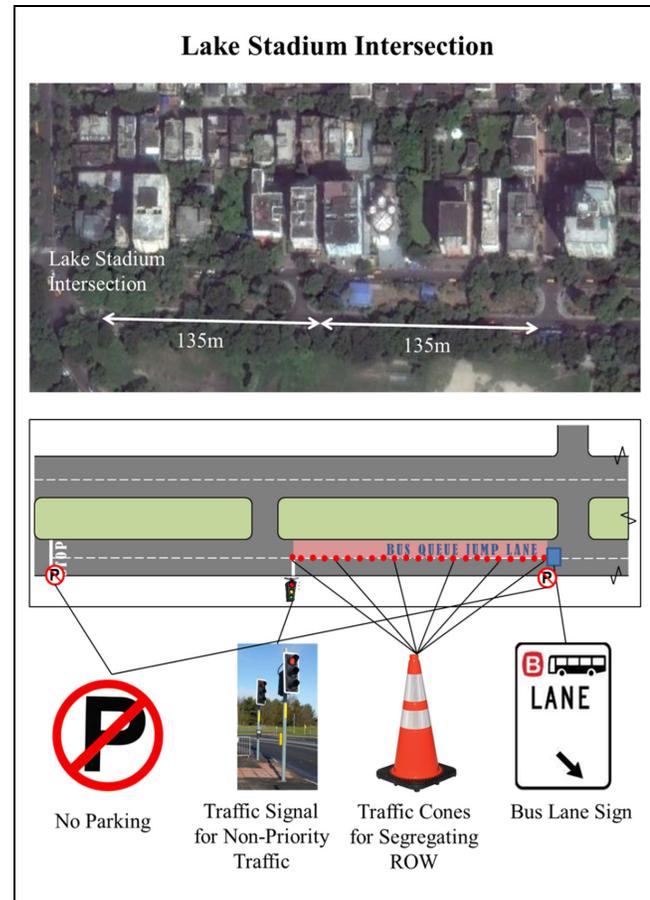


**Figure 2** (a) Traffic composition and (b) Desired bus movement for Southern Avenue.

during the implementation to guide the road users, if required, as per the rules and signages related to the QJL and pre-signal operations. Video cameras were placed at several locations along the corridor to investigate the traffic operations for a period of 4 hours from 07:00 to 11:00 to cover both the morning peak and off-peak period. The intersection-specific characteristics and the implementation plan are discussed in the following subsections.

### Southern Avenue (Lake Stadium Intersection)

Southern Avenue is a 4-lane divided corridor with two lanes in each direction. The westbound approach, which has a peak hour demand of approximately 1200 Passenger Car Unit per hour (PCU/h), was considered



**Figure 3.** Bus priority implementation plan for Southern Avenue.

for the case study and bus priority implementation. M2Ws and cars predominantly share the traffic stream with the bus share being around 5%. Figure 2a shows the traffic composition in the Southern Avenue approach. The majority of the buses (64%) make a right turn while the rest make through movement (36%). The bus stops are located on the far side of the intersection. Due to the turning movements and absence of nearside bus stops, the buses prefer to use the medianside lane, as shown in Figure 2b, in order to maintain higher speeds and to facilitate an easier manoeuvre. There is a median opening about 130 m upstream of the intersection STOP line where there is a significant U-turning vehicle movement. The traffic signal at the Lake Stadium intersection operates on a 120 s cycle length with 50 s green time for the westbound approach of Southern Avenue.

Considering predominantly right-turning bus movements and the left-hand driving principle in the Indian subcontinent, the bus QJL is provided on the medianside lane to facilitate bus movements and to allow the buses to maintain their desired path. It was necessary to provide the QJL upstream of the median opening in order to allow the U-turning non-priority traffic to make the

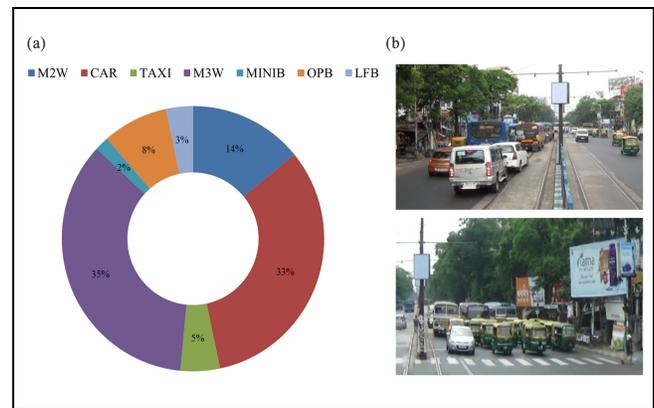


**Figure 4.** (a) Entry point and (b) Exit point for bus QJL at Southern Avenue.

manoeuvre. The layout and necessary infrastructure for the implementation of bus priority is shown in Figure 3. It was necessary to provide parking restrictions on the curbside to remove encroachments and allow unhindered access of non-priority traffic on the curbside lane. Traffic cones were used for delineation to segregate the bus right-of-way from the non-priority traffic. The pre-signal for non-priority traffic operates on the same cycle length as the main signal at the intersection. However, since the pre-signal is located at a distance of about 135 m from the STOP line at the intersection approach, the green time is initiated at the pre-signal 20 s prior to initiation of green time at the main signal. This is to ensure vehicle progression such that the number of stops is not increased for the non-priority vehicles waiting at the pre-signal. Figure 4 shows the entry and exit points of the bus QJL.

**Rashbehari Avenue (Deshapriya Park Intersection)**

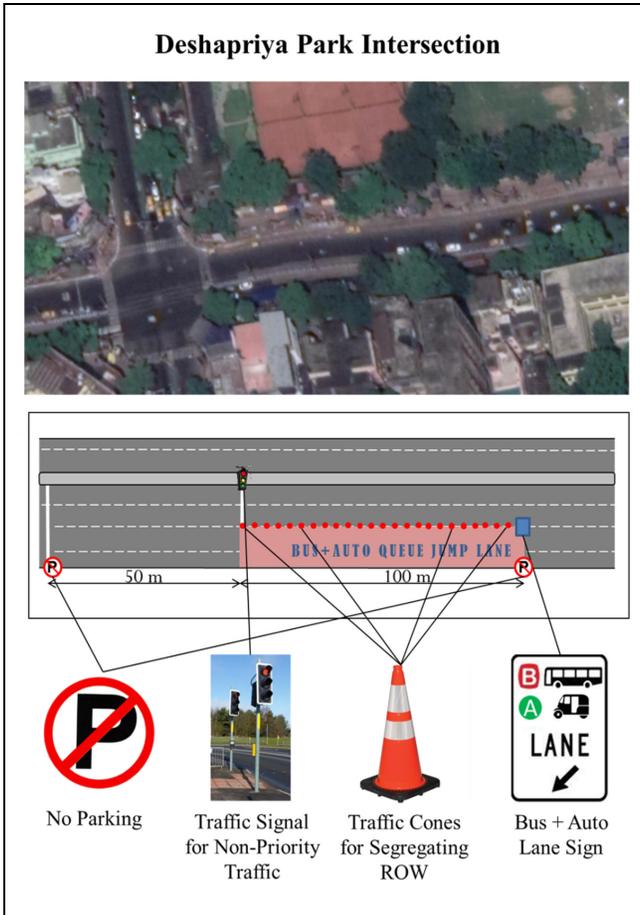
Rashbehari Avenue is a 6-lane divided corridor with three lanes in each direction. The westbound approach of Rashbehari Avenue has a peak hour demand of approximately 1400 PCU/h and was selected as the second study location. Here, the vehicle composition is more heterogeneous compared with the Southern Avenue approach. As shown in Figure 5a, the share of M3Ws (or tuktuk, or autorickshaw) is predominant at 35% with an arrival rate of more than six per minute. Buses also exhibit a higher share of about 13% in the vehicle stream with about 110 to 120 buses arriving per hour during the peak period. Bus movements are predominantly through and a nearside bus stop is located on the studied westbound approach. Therefore, in this case, buses need to access the curbside lane. However, due to a heterogeneous traffic mix buses are generally unable to access the bus stop, causing unsafe boarding and alighting practices among bus users. The



**Figure 5.** (a) Traffic composition and (b) Bus in mixed traffic for Rashbehari Avenue.

traffic signal operates on a 120 s cycle length with a 50 s green time for the through movement, followed by a 20 s green time for the right turning movement.

The bus QJL is provided at a distance of 50 m from the STOP line on the curbside to allow buses to access the nearside bus stop. It may be mentioned that auto-rickshaw acts as an Intermediate Public Transport (IPT) mode and serves more than three passengers on average, and also needs to access the bus stops for boarding and alighting of passengers. Therefore, in this context, the autorickshaw mode is also allowed to access the QJL. The layout and necessary infrastructure for implementation of bus priority is shown in Figure 6. It was necessary to provide parking restrictions on the curbside to remove encroachments and allow unhindered access of bus and autorickshaw on the QJL. In this case also the pre-signal for non-priority traffic was made to operate on the same cycle length as the main signal at the intersection. However, since the pre-signal is located at a distance of



**Figure 6.** Bus priority implementation plan for Rashbehari Avenue.

about 50 m from the STOP line at the intersection approach, the green time is initiated at the pre-signal only 10s prior to initiation of green time at the main

signal to ensure non-priority vehicle progression. Figure 7 shows the entry and exit points of the bus and auto-rickshaw QJL.

**Findings from QJL Implementation**

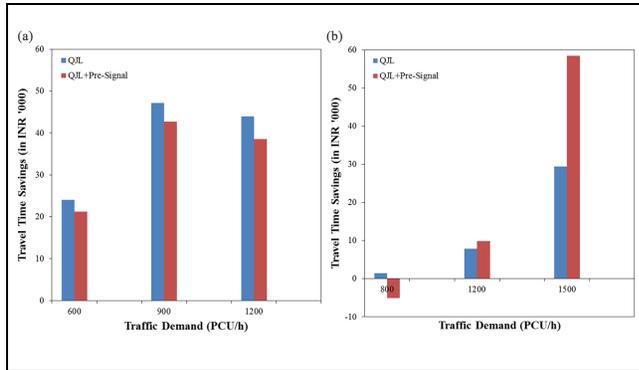
As mentioned in the previous section, the experiment was carried out in three phases at both the intersection approaches. The first phase involves the present scenario with no bus priority, followed by bus priority with only QJL in the second phase, and bus priority with QJL and pre-signal for non-priority vehicles in the third phase. There are manifold impacts of bus priority treatments. This paper presents the direct impacts of bus priority on both priority and non-priority traffic in terms of travel time, discharge, and dwell times. In the context of emerging countries such as India, it is also meaningful to investigate the social acceptance of the bus priority treatment. This aspect was investigated based on the violations related to right-of-way restrictions. All these findings are based on data recorded from high resolution video cameras placed on different locations along the study corridors.

**Impact on Travel Time**

The travel time impacts on priority and non-priority vehicles were investigated for both peak and off-peak periods for the two intersection approaches. The travel time sections were identified to investigate the change in travel time for clearing the intersection due to the implementation of bus priority. Therefore, they were considered from the upstream end of the QJL to 50 m downstream of the intersection. Varied impacts on travel time on different modes were observed for the two locations. While Rashbehari Avenue approach yielded about



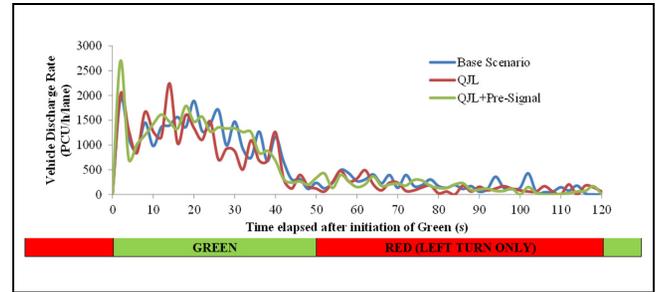
**Figure 7.** (a) Entry point and (b) Exit point for bus QJL at Rashbehari Avenue.



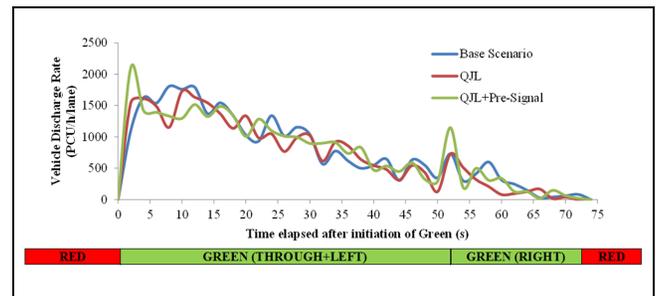
**Figure 8.** Passenger travel time savings at different demand levels for (a) Southern Avenue and (b) Rashbehari Avenue.

20% reduction in bus travel time and a marginal increase of about 6% in non-priority vehicle travel time during the peak traffic period, a 15% reduction and 20% increase in bus and car travel times respectively were observed for the same period in the case of Southern Avenue approach. This shows that the effectiveness of bus priority treatment is largely location-specific.

Vehicle occupancy surveys were carried out, and the overall impact in travel time on passengers as a whole was estimated considering an hour of operation during different traffic demands for all weekdays of a year. The travel time savings were quantified considering a willingness to pay of INR 0.98/minute of savings in in-vehicle travel time (11). The variation of impacts with respect to changing traffic scenarios among the two corridors under study is exhibited in Figure 8. Since the traffic flow values and the resulting travel time savings were directly obtained from the field, so the benefits obtained from the two scenarios at similar traffic demand could not be directly compared. However, the findings show a trend indicating the effectiveness of QJL and pre-signal in different scenarios. Implementation of QJL as a bus priority treatment was found to be more beneficial in lieu of QJL with pre-signal at the Southern Avenue approach. This is due to the additional negative impact on the high car share in the traffic stream due to installation of pre-signals. On the contrary, the implementation of bus priority with QJL and pre-signal becomes more effective during peak traffic periods because of the high share of public transport in the traffic stream of Rashbehari Avenue approach. These findings show that the priority treatments are effective under particular scenarios, and it is necessary to identify the optimal application of priority treatments in different traffic and control scenarios. A properly calibrated and validated traffic micro-simulation tool is necessary at this stage since it is infeasible to investigate the applicability of bus priority treatment under all such typical traffic scenarios in practice.



**Figure 9.** Vehicle discharge profile for Southern Avenue approach.



**Figure 10.** Vehicle discharge profile for Rashbehari Avenue approach.

### Impact on Vehicle Discharge

The vehicle discharge rate at the STOP line was measured at every 2 s interval for both intersection approaches. The vehicle discharge profile for the Southern Avenue approach is shown in Figure 9 while that for Rashbehari Avenue is shown in Figure 10. In both cases, it is observed that the initial discharge is higher by applying bus priority treatments in the form of QJL. Moreover, the initial discharge rate is even higher by implementing a pre-signal for non-priority traffic along with the provision of a QJL. Two factors may be considered to contribute to this change in the initial discharge. The first factor is that, since the buses are allowed to jump the queue, there is an increase of the probability that buses are among the first vehicles to discharge from the STOP line. The change in traffic composition (in percentage) in the first ten vehicles discharging from the Rashbehari Avenue approach during initiation of green is exhibited in Table 1. There has been about 8% increase in bus and M3W share with a similar decrease in car and M2W share. This change in traffic composition was not observed for Southern Avenue approach as bus share was much lower in the overall traffic stream. The second factor is that the non-priority vehicles are allowed to maintain progression by synchronizing the pre-signal with the main traffic signal, thus improving the quality of discharge.

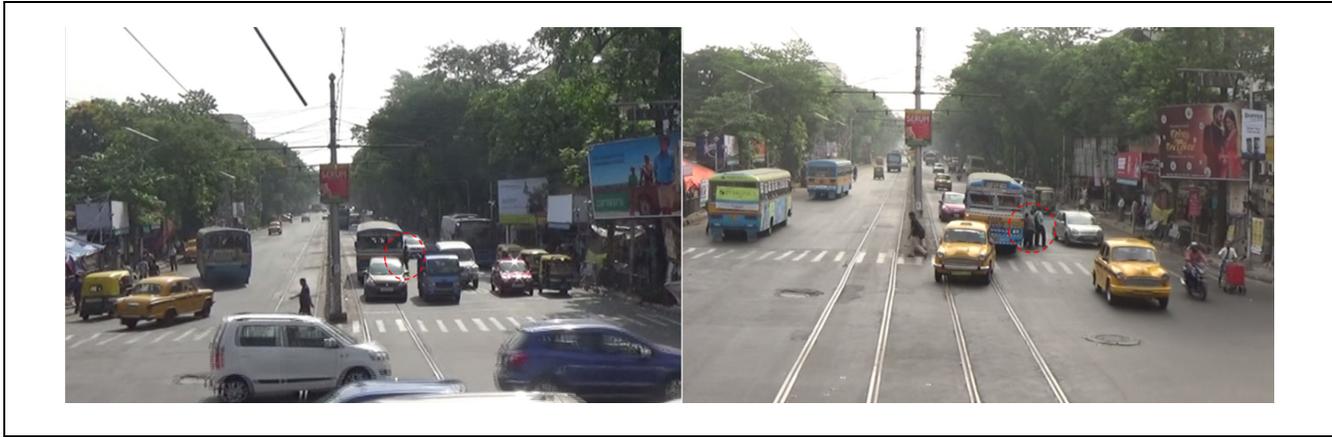


Figure 11. Unsafe boarding and alighting behavior at Rashbehari Avenue approach.

Table 1. Vehicle Composition (%) for First 10 Vehicles Discharging at Rashbehari Avenue Approach

Vehicle mode	Base scenario	Bus priority scenario
Car	33%	28%
M2W	15%	13%
M3W	43%	48%
Bus	8%	11%

Note: M2W = Motorized Two-Wheeler; M3W = Motorized Three-Wheeler.

### Impact on Passenger Boarding and Alighting

Two specific changes were observed at the nearside bus stop on Rashbehari Avenue due to implementation of QJL. Prior to implementation of QJL, the buses used to make stops away from the curbside resulting in unsafe boarding and alighting behaviour of bus users in the middle of the carriageway thus exposing them to the traffic flow. Some examples of such unsafe acts are demonstrated in Figure 11. About 20% of the buses used to perform such unsafe manoeuvres in the base scenario. However, due to the introduction of the QJL, buses are now restricted to using the curbside lane and this automatically ensures safe boarding and alighting behavior among 90% of the buses. In addition to safe boarding and alighting practices, there has also been an improvement in the dwell time of buses, as demonstrated in Figure 12 which shows a general shift towards shorter dwell time of buses by introduction of QJL. The average bus dwell time decreased from 6.6 s to 5.5 s by introduction of QJL, and further to 5.2 s by introduction of pre-signals along with QJL. There is also a reduction in the dwell time variability from 4.5 s to 3.8 and 3.2 s respectively. This improvement may be attributed to the fact that buses are forced to maintain a single queue along

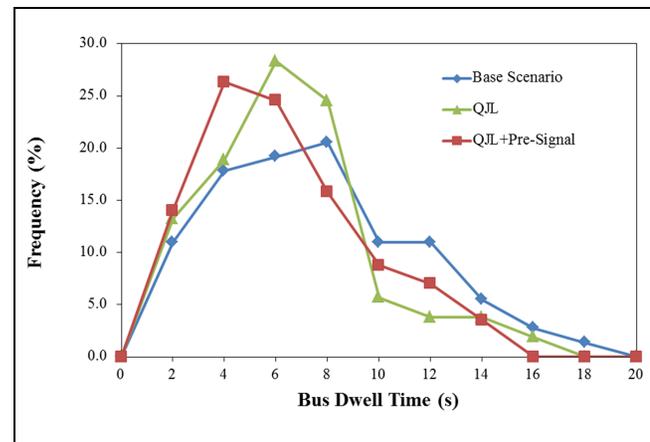


Figure 12. Bus dwell time distribution at Rashbehari Avenue approach.

the QJL, and the leading bus cannot waste additional time at the bus stop due to pressure from the following buses.

### Social Acceptability of QJL

In emerging countries such as India, road users are generally susceptible to violating the rules of the road primarily due to lack of awareness. Therefore, in the present context, with the introduction of a new traffic management system in the form of bus priority, it is necessary to observe the attitude of different road users towards QJL. The degree of violations of non-priority vehicle users and priority vehicle users are investigated separately for the two intersection approaches under study and are presented in tabular format and discussed below.

Table 2 shows the degree of violations by different modes for the westbound traffic on Rashbehari Avenue approach. It may be observed that M2Ws significantly

**Table 2.** Right-of-Way Violations for Rashbehari Avenue Approach

Violations by non-priority vehicle users (% of each vehicle type)								
Vehicle Type	QJL				QJL + Pre-Signal			
	Left	Through	Right	Total	Left	Through	Right	Total
Car	24.0	3.0	10.0	7.0	22.5	4.5	2.0	7.5
Taxi	26.0	10.5	0.0	12.0	30.0	7.5	0.0	10.5
M2W	72.5	33.0	12.5	37.5	55.0	24.0	35.0	30.0
Violations by priority vehicle users (% of each vehicle type)								
Vehicle Type	QJL				QJL + Pre-Signal			
	Left	Through	Right	Total	Left	Through	Right	Total
M3W	0.0	3.5	0.0	3.5	0.0	3.5	0.0	3.5
MiniB	0.0	7.0	31.5	14.5	0.0	2.5	5.0	3.5
OPB	0.0	2.5	20.5	7.5	0.0	1.0	7.5	3.0
LFB	0.0	5.0	0.0	5.0	0.0	0.0	0.0	0.0

Note: M2W = Motorized Two-Wheeler; M3W = Motorized Three-Wheeler; MINIB = Mini Bus; OPB = Ordinary Private Bus; LFB = Low Floor Bus.

**Table 3.** Right-of-Way Violations for Southern Avenue Approach

Violations by non-priority vehicle users (% of each vehicle type)								
Vehicle Type	QJL				QJL + Pre-Signal			
	Left	Through	Right	Total	Left	Through	Right	Total
Car	4.0	4.5	0.5	4.0	3.0	1.5	3.0	2.5
Taxi	0.0	4.5	0.0	3.0	1.0	2.0	0.0	1.5
M2W	3.0	4.0	9.0	4.5	3.5	4.5	5.5	4.5
Violations by priority vehicle users (% of each vehicle type)								
Vehicle Type	QJL				QJL + Pre-Signal			
	Left	Through	Right	Total	Left	Through	Right	Total
OPB	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LFB	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Note: M2W = Motorized Two-Wheeler; OPB = Ordinary Private Bus; LFB = Low Floor Bus.

violate the right-of-way restrictions. This may be because the QJL is provided on the curbside and M2W users, being vulnerable road users, prefer to use the curbside lane on a 3-lane road for safety reasons. Furthermore, left-turning non-priority vehicles are more prone to violate the restrictions. Therefore, it is necessary to consider the placement of QJL where there is substantial left-turning non-priority traffic or two-wheeler traffic. Among the priority modes, a small portion of autorickshaws tend to violate the QJL which may be caused by a high demand of M3Ws with an arrival rate of more than six vehicles per minute. A fraction of the right turning buses have violated the QJL with the concerns for being unable to negotiate a right turn from the curbside QJL

although a sufficient length of 50m was provided near the intersection approach for these buses to advance and safely negotiate a right turn. There is a reduction in violations for all modes on the next day of implementation with pre-signal alongside QJL which shows a positive attitude of road users towards the implemented bus priority measure. The right-of-way violations for the west-bound traffic in Southern Avenue approach is shown in Table 3. The violations are much lower in this case due to a more homogeneous mix in the traffic stream with predominant car share as compared with the previous corridor. In this case also, the violations were reduced while moving forward from Phase 2 to Phase 3 of implementation.

## Conclusion

This paper brings out several interesting and valuable observations derived from the practical implementation of bus priority treatments with QJL and pre-signal at urban signalized intersections with mixed traffic operations. Two representative corridors were selected for the implementation of bus priority in three phases, and the findings clearly indicate their applicability and effectiveness under different scenarios.

The design of the bus QJL and pre-signal was obtained from the micro-simulation framework, and the same design could be directly implemented successfully in the field without much modification. This indicates the strength of using traffic flow micro-simulation for investigation and evaluation of alternative strategies prior to field implementations.

The field implementation indicated travel time savings to passengers as a whole for both investigated approaches. However, there was variation in benefits with regard to different scenarios which indicates the need to identify the effective domains of application for specific bus priority treatments.

While impacts from the bus priority implementation on travel time and vehicle discharge yielded the effective benefits of QJL and pre-signals, it was also meaningful and interesting to investigate the impacts on driver behavior in terms of bus stop manoeuvre, and social acceptability during the field trials of such implementation. The decrease in violations over time indicated a positive attitude of road users towards the bus priority treatment. The experiment has been carried out on a short-term basis for a span of three days only considering each location. Therefore, the reduction in violations over such a short span also indicates that the current bus priority system may be effective and successful in terms of road user compliance once it is implemented as a permanent long term measure. Implementation of bus QJL resulted in a change of the bus driver attitudes, leading to a reduction in dwell time and safer boarding and alighting. The changes in safety-related aspects and driver violations are several aspects which may not be directly obtained from investigation in an analytical or micro-simulation platform.

Altogether, the implementation of bus priority with QJL and pre-signal yielded considerable benefits in several aspects and different segments of road users have also showed positive attitude towards the experiment. These results have even encouraged the local traffic management and law enforcement personnel to seriously consider implementing this bus priority system as a permanent measure at several strategic locations of the Kolkata metropolitan city. Once the present bus priority system is implemented as a long-term permanent measure, it will also become meaningful to investigate the

perceptions of different stakeholder groups to develop a more in-depth understanding of the societal impacts and acceptance of such initiatives in the current context. The successful implementation of bus QJL with pre-signal is also expected to encourage practitioners to apply similar bus priority treatment in other Indian cities as well as in other cities in emerging countries with analogous traffic operations. Moreover, the overall experience as documented in this paper might encourage researchers to adopt a similar approach to investigate the feasibility of different transportation projects beyond an analytical or simulation platform.

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## Author Contributions

The authors confirm contribution to the paper as follows: Study conception and design: BM, MB, KB; data collection: KB; analysis and interpretation of results: KB, BM, MB; draft manuscript preparation: KB. All authors reviewed the results and approved the final version of the manuscript.

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