An innovative dynamic bus lane system and its simulation-based performance investigation

The MIT Faculty has made this article openly available. Please share how this access benefits you. Your story matters.

<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>As Published</td>
<td><a href="http://dx.doi.org/10.1109/IVS.2009.5164261">http://dx.doi.org/10.1109/IVS.2009.5164261</a></td>
</tr>
<tr>
<td>Publisher</td>
<td>Institute of Electrical and Electronics Engineers (IEEE)</td>
</tr>
<tr>
<td>Version</td>
<td>Final published version</td>
</tr>
<tr>
<td>Accessed</td>
<td>Tue Dec 11 17:43:52 EST 2018</td>
</tr>
<tr>
<td>Citable Link</td>
<td><a href="http://hdl.handle.net/1721.1/71876">http://hdl.handle.net/1721.1/71876</a></td>
</tr>
<tr>
<td>Terms of Use</td>
<td>Article is made available in accordance with the publisher's policy and may be subject to US copyright law. Please refer to the publisher's site for terms of use.</td>
</tr>
<tr>
<td>Detailed Terms</td>
<td></td>
</tr>
</tbody>
</table>
An Innovative Dynamic Bus Lane System and Its Simulation-based Performance Investigation

Hong Yang
Civil and Environmental Engineering
Rutgers, The State University of New Jersey
Piscataway, NJ 08854
Email: yanghong@eden.rutgers.edu

Wei Wang
Civil and Environmental Engineering
Massachusetts Institute of Technology
Cambridge, MA 02139
Email: wwangcee@mit.edu

Abstract—The strategy of exempting bus from other traffic through exclusive bus lanes (XBL) is prevalent. Rather than just deploying the XBL system, in this study, a new innovative dynamic bus lane (DBL) operation system which is expected to be more productive is initially introduced. Unlike conventional studies which are mainly focused on operational performance of buses, this study attempts to examine the influences on buses and adjacent traffic following the provision of both XBL and the new system. Impact measurements in terms of travel time and traffic conflicts changes are used as assessment indicators. Comparisons with the exclusive bus lane system as well as the mixed traffic flow are analyzed and highlighted through the application of micro-simulation approach. Simulation results showed that both XBL and DBL have positive impact on buses and negative impact on adjacent traffic. Traffic conflicts frequency will increase if either bus lane system is applied. Also it is found that DBL performs better than XBL in terms of achieving the goal of bus operation improvement while limited the performance deterioration to other vehicles and conflicts risks in a relative lower magnitude. Results also suggest the necessity of selecting the optimal strategies according to the tradeoff between the operational performance and safety performance under different traffic conditions.

I. INTRODUCTION

Traffic congestion is a common phenomenon that experienced in many urban areas around the world due to the increase in travel and number of vehicles. This issue can be primarily attributed to the limited transportation system supply that does not satisfy the increasing traffic demand. Simply, the road space increasing is unable to keep up the rapid growth of vehicular traffic. Land-use and travel behavior change may also encourage the travel mode shifting from public transport towards private traffic. As intensive augmentation and enhancement of transportation infrastructures supplement usually will be uneconomical, alternative solutions to the congestion issue is expected. Realizing the potentials of existing resources can be a practical way to achieve the goal of efficiently delivering more passengers and goods. Among the measures that have been identified and implemented in field, innovative bus priority systems are regarded as desirable treatments to enhance bus attractiveness and promote the shift of travel mode from cars to buses, which in turn will finally result in relaxation or disappearance of traffic jam.

One of the most common priority systems so far is the application of exclusive bus lane (XBL). By allocating a reserved lane on arterials to exempt buses from other private traffic, bus service quality in terms of travel speed, travel time reliability, etc, are anticipated to be well secured by XBL. Operation performances of XBL have been widely reported based on the feedback from practices. However, the impact of provision of XBL on adjacent traffic is not always reported at the same level of detail. For an optimal system, it is necessary to establish the balance of the entire system based on a completely investigation of its performance and impact. But current major understanding of deploying XBL system still limited the scope within its operation performance. There is still no adequate understanding of its performance other than the operational aspect. Since the system is primarily designed with a preference of bus operation, intuitively, it unavoidably has negative impact on the quality of other adjacent traffic.

To realize the full potentials of XBL, it is necessary to display its advantages as well as disadvantages for better system design. In the meanwhile, identifying the distinctive features of XBL is also beneficial for making improvement or seeking better system without great effort. Therefore, the specific objectives concerned in this study are mainly focused on twofold:

1) Other than operational performance of bus, the impact of provision of XBL on adjacent traffic as well as system safety performance will also be investigated using simulation model;

2) An innovative bus priority system based on the extension of XBL concept is introduced and its performance both in operation and safety aspects will be highlighted by comparing with XBL.

The following sections of paper are sequentially organized as follows: A comprehensive review of related studies and practices deploying exclusive bus lane is presented in section 2. Section 3 describes the structure of newly proposed bus priority system. Section 4 illustrates the study approach and measures on investigating bus as well as
adjacent traffic performance. Based on the running of experiments, test results and analysis are addressed in the fifth section. Finally, the findings are summarized and future potential work is discussed.

II. LITERATURE REVIEW

The impact of provision exclusive bus lanes are frequently discussed in the literature. Several studies conducted before-and-after comparisons of XBL to identify the performances of XBL on urban networks in the United States, India, China as well as South Korea, etc. Both successful and unsuccessful results were obtained after the implement of XBL. For instance, Erdman et al. (1976) performed an investigation to study the impact of XBL on a two-directional roadway with two lanes in each direction in Baltimore metropolitan area. It was found that the average travel time for major commuters in the morning peak period using bus lane rather than a passenger car was determined to be 50 percent longer than before. The authors concluded that the XBL was detrimental to both automobile and bus movements in terms of travel time. Similarly, Sarin et al. (1983) evaluated the XBL system, which was first introduced in Delhi, India, in 1976. The study revealed that the system failed to save travel time as a consequence of ineffective enforcement. The system was discontinued in 1981. The first XBL was implemented in Kunming, China, in 1999. Wei et al. (2002) compared its performance before and after 2 years operation. It was found that the average speed of bus increased 68%, from 9.6km/h to 15.2 km/h. The corresponding impact on other vehicles was not reported. Choi et al. (1995) conducted their study in South Korea and argued that the XBL system was successful. Bus travel time was significantly reduced, a mode shift from car to bus was estimated to be more than 12%, and accident rates were reduced. Similar positive impact of XBL in South Korea was further illustrated by the study of Kim (2003). His survey showed that the XBL were successful in improving average bus performance compared with other adjacent traffic in terms of relative speed changes. Rather than focusing on bus operation performance, Karim (2003) evaluated the effect of XBL on travel time of other modes using floating car technique. It was found that the mean travel time for other vehicles are significantly increased after the executing bus lane during morning and evening peak hours.

Due to the long cycle of conducting before-and-after comparison, simulation method also has been used in recent years as an alternative for the purpose of operational analysis of XBL. Shalaby (1999) applied the TRANSYT-7F simulator to investigate the impact of provision of the reserved bus lanes on through buses and other traffic in an urban arterial in downtown Toronto, Canada. Currie et al. (2004) proposed a balanced framework for roadway space reallocation associated with transit priority. Simulation model was deployed to clarify the operational performance of transit priority measures. In their latest study [9], the methodology to assess trade-offs in the use of the limited road space in Melbourne, Australia for new bus and tram priority projects is introduced. Again, micro-simulation model was used to examine road space reallocation impacts. Mori et al. (2006) using simulator NETSTREAM evaluated the use of exclusive bus lanes on Nagoya-Seto Expressway which is the main expressway link from the Tomei Expressway in Japan. EBL running strategy during the Expo 2005 was suggested according to their findings. Arasan et al. (2008) investigated the impact following the introduction of XBL on the highly heterogeneous traffic flow on urban roads using the micro simulation model HETEROSIM.

It is clear from the review of previous studies that most of the efforts have been focused on the operational performance of buses either by before-and-after comparison or simulation test. Impacts of XBL on adjacent traffic operation as well as the safety performance to date have been limited, which is important to assist in understanding the essential benefits of XBL. Since bus does not interact or conflict with other vehicles, its operational improvement is easily to be expected. However, the space taken away from mixed traffic would create congestion or more conflicts due to lane availability constraints on other vehicles, which might lead to an inefficient and unsafe operation of the traffic. To justify the efficiency and safety performance of bus priority system, it is necessary to make more efforts on comprehensively investigating their potential impact. Then improvements can be made accordingly.

III. THE STRUCTURE OF DYNAMIC BUS LANE

In this study, we propose a dynamic bus lane (DBL) operation system. The new concept of our dynamically assigned bus lane is designed as shown in the following Figure 1 where the rightmost lane is reserved for buses (yellow color) under certain traffic situations. When there is no bus coming, the curbside lane is open to all the traffic as shown in Figure 1(a). When a bus is detected, the downstream curbside lane (between intersections 11 and 12) is then temporarily restricted for buses only. Vehicles ahead of the bus which are already travelling on the reserved bus lane can keep flowing within the lane or it could change lanes towards the other lanes on the left side. However, vehicles on the other lanes are restricted from accessing to the bus lane ahead of the bus. This is ensured by activating the warning signs along the midline to remind private vehicles on the left lane. The Figure 1(b) demonstrates such situation as the other vehicles following buses have to change lane once the bus is detected approaching. One specific occasion is that for those right-turn vehicles, they are allowed to travel on the reserved bus lanes with buses. To implement the dynamic bus lane, the following technique components are required, such as Automatic Vehicle Location (AVL) system or loop detectors (to detect bus); vertical variable message signs (VMS) to disseminate rightmost lane usage information (to other vehicles); and the horizontal in-pavement lighting system as dynamic roadway markings to remind the drivers on adjacent lanes. The VMS could be set at the upstream intersection approach lane. According to the link length, multiple VMSs must be installed along the link to ensure drives get the message and
have sufficient time to make their decision. It is assumed that all drivers would obey the lane-changing rule once they see the posted VMS information of lane restriction.

As shown in Figure 1 (b), in this study, bus arrival is assumed to be detected by the loop detector at upstream link. Also it should be noted that all the traffic signal control strategies are not modified to provide priority for buses. Compared to the XBL, the DBL is expected to achieve similar objective of improving bus service in a more efficient way. Deploying DBL system, roadway resources are expected to be allocated in a productive manner.

![Figure 1 Structure of the dynamic bus lane](image)

**IV. PERFORMANCE ASSESSMENT APPROACH**

Previous practices can only provide us some experience of XBL’s operational performance. But there are still no specific studies reporting some safety evaluation hints about the strategies. Also for the new proposed DBL system, it is important to determine its effect compared to the mixed traffic flow as well as XBL. To obtain a better understanding of the two strategies, this study applies a simulation-based assessment approach to highlight their performances. Paramics is selected as the micro-simulation tool to support the study. The major reasons encourage us to apply this test platform are: First, customizable models can be obtained through the Application programming Interface (API), which is a significant advantage over most other simulators. Second, its potentials to be applied for safety evaluation based on surrogate safety measures analysis [12]. Customized API which activates and deactivates the utilization of DBL is programmed to make the bus lanes behave in a dynamic way as stated in previous section.

With the principal objective of quantifying the impacts of different strategies on traffic, two measurements are used for the purpose: average travel times and traffic conflicts. The former one is frequently used as conventional indicator to determine the operation performance, and the latter is applied to highlight the safety performance. The traffic conflicts in this study are identified by the modified time-to-collision (MTTC), which was introduced by Ozbay et al. (2008). Detail description of the simulation-based safety analysis approach can be referred in the study.

To make the results comparable, different networks including mixed-traffic, exclusive bus lane and dynamic bus lane design are modeled for test. All the influential parameters such as driver behaviors, speed limits, and signal timing are assumed to be the same among the networks to avoid mixing their influences with the operation strategies. Experiments of different test scenarios are listed in Table 1.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Options</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of System</td>
<td>Mixed, XBL, DBL</td>
</tr>
<tr>
<td>Link Length (m)</td>
<td>1000m with 3 lanes</td>
</tr>
<tr>
<td>Bus Volume (veh/h)</td>
<td>30, 60, 90, 120, 150, 180</td>
</tr>
<tr>
<td>Non-Bus Volume (veh/h)</td>
<td>500, 700, 900, 1100, 1300, 1500, 1700, 1900, 2100, 2300, 2500, 2700, 2900, 3100, 3300</td>
</tr>
</tbody>
</table>

Considering the stochastic nature of the simulation model, multiple runs must be conducted in order to get statistically reliable results from the simulation experiments. The simulation runs of each scenario with different random seeds are identified using the sequential approach. This statistical procedure aims at obtaining the mean \( \mu = E(X) \) of the selected measures of effectiveness (MOE) \( X \), within a specified precision. If we estimated \( \bar{X} \) such that \( |\bar{X} - \mu|/\sigma = \gamma \), then \( \gamma \) is called the relative error of \( \bar{X} \). The specific objective of this approach is to obtain an estimated \( \mu \) with a relative error of \( \gamma \) and a confidence level of 100(\( 1 - \alpha \)) percent. Denote the half-length of the confidence interval by \( \delta(n, \alpha) \). Further details about the approach are presented as follows [13]:

1. Make an initial number of \( n_0 \) replications of the simulation and set \( n = n_0 \), then calculate initial (crude) estimates \( \bar{X}(n) \) and \( S^2(n) \) from \( X_1, X_2, \ldots, X_n \);  
2. Decide the size of allowable relative error \( \gamma = |\bar{X} - \mu|/\sigma| \);  
3. Calculate the adjusted relative error \( \gamma' = \gamma/(1 - \alpha) \);  
4. Decide the level of significance \( \alpha \);  
5. Calculate the half-length of the confidence interval \( \delta(n, \alpha) = t_{n-1, \alpha/2}/\sqrt{S^2(n)/n} \);  
6. If \( \delta(n, \alpha)/|\bar{X}(n)| \leq \gamma' \) use \( \bar{X}(n) \) as the point estimate for \( \mu \) and stop, else make one more replication and set \( n = n + 1 \), then go back to step 2.

This approach assumes identical, independent (IID) outcomes, but they need not be normally distributed. Thus the estimates of \( \bar{X}(n) \) and \( S^2(n) \) for the mean and variance,
as well as the estimation quality improved with the incremental iteration.

A relative error of $\gamma = 0.05$ and a confidence level of 95% are used to examine the effectiveness of replications. In our case, 9 random seeds are found to satisfy the requirement, and the average results of each scenario are then used for further comparison analysis.

V. RESULTS AND ANALYSIS

The simulation outputs that measure the influence of different bus lane operation strategies on operation performance and safety of the vehicles are analyzed for each simulated scenario. The analysis of variance (ANOVA) is used to statistically test the differences among the strategies. The results are reported based on a significant level of p-value=0.05. Vehicles that traversed the 1000m study section are used in the data aggregation.

Figure 2 demonstrates an example of bus and car travel time changes under different operation strategies. It is clearly to see that DBL and XBL almost equivalently decrease the bus travel time compared to mixed traffic flow. And DBL performs better in terms of the impact on other vehicles’ travel time increment.

Table 2 summarizes the average travel time of bus and other vehicles for all six simulated scenarios. The results indicated that both XBL and DBL are relatively beneficial since it results in shorter travel time of bus compared to the mixed traffic operation. Also these two strategies almost achieve the similar level of bus travel time improvement as the p-values show no significant differences though DBL yields slightly shorter travel time. Regarding the impact on adjacent traffic, the results in Table 2 indicate that either XBL or DBL will have negative influence by increasing the travel time. In addition, when bus volume is lower than 120veh/h, DBL performs better as its impact is less serious than that of XBL. Once the bus volume is heavy, DBL is almost equivalent to XBL. These results might be attributed to the fact that the adjacent vehicles will have few chances to utilize the curbside lane if the bus lane is frequently used by bus. It is worth noting that the travel time of bus is more stable regardless of increase in traffic flow. This is attributed to the exemption of buses from other traffic disturbance. And the travel time of adjacent traffic will increase with increase of traffic flow due to reduction of accessible lanes. All these findings provides the hint that DBL could be a better alternative to efficiently allocation of the roadway resources.

The average traffic conflicts rate for each vehicle is used as a surrogate measure of safety. Figure 3 shows an example of demonstrating the different impact of the strategies. Briefly, both DBL and XBL will increase the conflict frequency significantly.

Table 2 Differences of average travel time

<table>
<thead>
<tr>
<th>Comparison</th>
<th>Changes</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
<th>Scenario 4</th>
<th>Scenario 5</th>
<th>Scenario 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>DBL vs. XBL</td>
<td>Decrease</td>
<td>0.52%</td>
<td>1.40%</td>
<td>1.76%</td>
<td>2.01%</td>
<td>2.33%</td>
<td>2.38%</td>
</tr>
<tr>
<td>(Car) P-Value</td>
<td>0.01386</td>
<td>5.053e-07</td>
<td>5.252e-09</td>
<td>1.363e-08</td>
<td>1.231e-09</td>
<td>6.648e-08</td>
<td></td>
</tr>
<tr>
<td>XBL vs. MIX</td>
<td>Increase</td>
<td>3.585e-11</td>
<td>3.515e-07</td>
<td>8.947e-05</td>
<td>0.008406</td>
<td>0.1288</td>
<td>0.3276</td>
</tr>
</tbody>
</table>

Figure 3 Traffic conflicts changes under different operation strategies
Table 3 presents the frequency differences of traffic conflicts among vehicles. A closer look on the conflict difference shows that DBL performs better as it reducing vehicles’ exposure to conflicts compared to XBL under the case of lower bus volume. However, when bus volume increased, the differences in conflicts rate among vehicles on roadways approach to the same magnitude regardless of the type of bus lane system imposed. This may be attributed to the fact that DBL act as XBL given the high frequency of bus arrival. In all scenarios the number of conflict rate increases with the increase of traffic flow. Due to the reduction of lane availability and increasing density, adjacent traffic will have fewer opportunities to change lanes to avoid some conflicts compared to all lanes accessible case. These results suggest that the probability of conflict risk is deteriorated when both XBL and DBL are deployed as an operation system on the street, but DBL is more likely to yield fewer conflicts which may result in traffic crashes.

Table 3 Average traffic conflicts rate difference

<table>
<thead>
<tr>
<th>Comparisons</th>
<th>Changes</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
<th>Scenario 4</th>
<th>Scenario 5</th>
<th>Scenario 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>DBL vs. XBL</td>
<td>Increase</td>
<td>19.61%</td>
<td>35.03%</td>
<td>40.17%</td>
<td>44.21%</td>
<td>47.03%</td>
<td>49.64%</td>
</tr>
<tr>
<td></td>
<td>P-Value</td>
<td>1.251e-07</td>
<td>3.995e-12</td>
<td>2.027e-11</td>
<td>1.021e-10</td>
<td>4.33e-11</td>
<td>1.824e-11</td>
</tr>
<tr>
<td>XBL vs. DBL</td>
<td>Increase</td>
<td>34.02%</td>
<td>53.89%</td>
<td>52.40%</td>
<td>52.39%</td>
<td>51.10%</td>
<td>50.07%</td>
</tr>
<tr>
<td></td>
<td>P-Value</td>
<td>3.597e-10</td>
<td>8.792e-12</td>
<td>4.499e-10</td>
<td>2.021e-10</td>
<td>4.33e-11</td>
<td>1.824e-11</td>
</tr>
<tr>
<td>DBL vs. XBL</td>
<td>Decrease</td>
<td>-22.21%</td>
<td>-12.19%</td>
<td>-8.05%</td>
<td>-5.27%</td>
<td>-2.69%</td>
<td>-0.33%</td>
</tr>
<tr>
<td></td>
<td>P-Value</td>
<td>3.597e-10</td>
<td>8.792e-12</td>
<td>4.499e-10</td>
<td>2.021e-10</td>
<td>4.33e-11</td>
<td>1.824e-11</td>
</tr>
</tbody>
</table>

VI. CONCLUSIONS AND FUTURE WORK

This study used a simulation approach to investigate changes in performance measures of buses and adjacent traffic following the deployment of different bus lane strategies. The following are the important contributions and findings of this study:

- Previous studies and practices provide some experience to understand the operational performance of executing exclusive bus lane. But not too many efforts have been done to quantify the impact of the specifically reserved bus lane system on other vehicles of adjacent lanes. Safety performance associated with the implementation of the system is still far beyond to be clarified.

- A new bus lane system named dynamic bus lane (DBL) is proposed and the simulation model is developed to test and compare the impact of exclusive bus lane (XBL) and the new system.

- It has been found through the study that both XBL and DBL is beneficial to significantly reduce the bus travel time. However, they all unavoidably have negative impact on adjacent traffic in terms of travel time increment. The magnitude of influence increase with the increase of traffic flow. The analysis of changes in operational performance shows that DBL system will perform better given a relative lower bus arrival frequency. This would be attributed to more efficient lane allocation system using DBL.

- Safety performance of providing XBL and DBL is evaluated using traffic conflicts as a surrogate safety measure. This is the first attempt to highlight the potential impact of different bus priority strategies from safety aspect, which was usually neglected or ignored. The conflicts frequency is found to get detonated with the increase of traffic flow. Also deploying DBL will yield less risks compared to the XBL system if there are still great opportunities for adjacent traffic using the bus lanes.

- Optimal tradeoff among the operational performance of buses and cars as well as their safety performance need to be considered regardless of which type of bus lane system is to be implemented. A balanced decision could be suggested given the traffic flow conditions (i.e. bus volume, other traffic flow) as discussed in the study.

This study is attempted to determine the impact of a new proposed bus lane system compared to conventional exclusive bus lane. Since it is a new concept and no practice experience is available, simplified simulation model is applied to demonstrate the capability of the suggested design. More calibration efforts of the model are expected to be discussed given the availability of field data in future. The impact of the system configuration such as number of lanes, bus stop, traffic signal, VMS and detector location, etc, deserves further investigation. The authors are currently involved in the study of such kind issues to further highlight the features of the bus priority systems.

REFERENCES


