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Improve Intersection Efficiency and Reduce Fuel Consumption with Shared BRT Lanes

Chunsheng Wang[1], Bo Yang[1], Yuan Cao[1*]

1 School of Automation, Central South University, Changsha, China

(*Corresponding Author: caoyuan3116@csu.edu.cn)

ABSTRACT

Bus Rapid Transit (BRT) is a popular transit priority measure that is widely implemented. However, when BRT lanes are not frequently used, it can negatively impact the efficiency of signalized intersections, leading to increased vehicle fuel consumption and environmental pollution. This study proposes the innovative strategy of implementing shared BRT lanes at intersections to address these challenges, and evaluates its effectiveness using various metrics. The findings demonstrate that shared BRT lanes significantly improve traffic efficiency, reduce vehicle fuel consumption. Furthermore, this approach offers a sustainable solution by conserving energy resources and mitigating environmental pollution, thereby highlighting its practical applications in urban transportation planning.

Keywords: shared BRT lanes, environmental pollution, traffic efficiency, vehicle fuel consumption, sustainable transportation

NONMENCLATURE

Abbreviations	
L	Congestion threshold
(x,t)	BRT real-time location
$X(t)$	Number of vehicles in the RL
$Y(t)$	Number of vehicles in the SBL
λ	Traffic flow in RL
M	Length of green light
$\bar{f}_a$	Vehicle FC during acceleration
$\bar{f}_d$	Vehicle FC during deceleration
C	Signal cycle
$K(t)$	State of the signal at time t
$E(IS)$	Expectations of Bus Arrival
$\bar{f}_i$	Vehicle FC during idling

1. INTRODUCTION

Bus Rapid Transit (BRT) is a popular measure in urban public transportation systems aimed at enhancing efficiency, sustainability, and attractiveness [1-3]. However, the use of BRT lanes poses several challenges, such as infrequent operation leading to inefficient traffic flow at intersections and increased vehicle fuel consumption [4,5].

Most of the current research in the field is primarily centered around bus priority signal control studies that has addressed transit delays [6-8]. However, there is a significant issue with underutilization of BRT lanes in the case of lower frequency BRT systems. This underutilization not only reduces the efficiency of the BRT system, but also increases the traffic burden and congestion costs [9,10].

To overcome these challenges and further improve the efficiency and sustainability of BRT systems, we propose an innovative strategy: implementing shared BRT lanes at intersections. This strategy entails sharing BRT lanes with other transportation modes to enhance traffic efficiency, reduce vehicle fuel consumption, and maintain the priority of public transportation.

This paper aims to assess the effectiveness of the shared BRT lane strategy in improving transportation efficiency and minimizing environmental impacts. Various metrics will be employed to evaluate its efficacy and compare it with traditional BRT lane options. Furthermore, this strategy promotes sustainability by conserving energy resources, mitigating environmental pollution, and providing a viable and sustainable solution for urban transportation planning.

This paper is structured as follows: Section II describes the operational process of shared BRT lanes and their induced signals. Section III presents the evaluation model and performance metrics used to assess the system. The results and analysis obtained are

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presented in Section IV, and the conclusions of the paper are demonstrated in Section V.

2. DESCRIPTION OF THE SYSTEM

This section introduces a novel shared BRT lane strategy aimed at improving signalized intersection efficiency, mitigating traffic congestion, and reducing vehicle fuel consumption. The strategy focuses on a scenario involving an isolated signalized intersection with two lanes: a dedicated BRT lane and a regular lane.

To implement this strategy, two crucial factors are taken into consideration. Firstly, the congestion level of the regular lane is assessed based on the length of the vehicle queue. The second is the use of real-time location information of buses. By employing these factors, a mobile guidance signal, such as a barrier, is strategically placed at the convergence point of the BRT and regular lanes.

The purpose of this mobile guidance signal is to direct the regular vehicles towards the BRT lane, effectively encouraging the utilization of the shared lane. This not only optimizes the use of available road space but also ensures that regular vehicles efficiently merge into the BRT lane without impeding the flow of BRT vehicles.

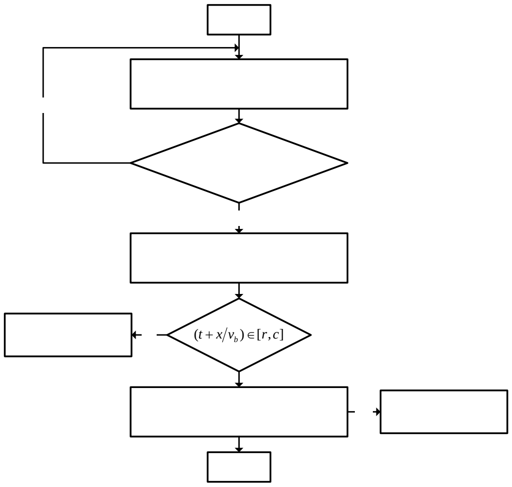

Fig. 1. Shared BRT Lanes and the Induced Signal Operation Processes

The operational process of the mobile guidance signal is illustrated in detail in Fig. 1. By implementing this strategy, the overall efficiency of the signalized intersection can be significantly enhanced, leading to improved traffic flow, alleviation of congestion, and reduced fuel consumption for vehicles.

3. *MATERIAL AND METHODS*

3.1 Stochastic Queuing Model

In this section, we present a stochastic queuing model. In order to effectively capture the vehicle queuing process. It follows the following assumptions: (1) The green light (red light) can be considered as composed of $M(N)T$ time intervals, only one vehicle is allowed to depart in each time interval T. (2) The arrivals of vehicles are random and independent, following a Poisson distribution.

For any $t > 0$, let's define the system state at time t as $(X(t), Y(t), K(t))$. Let $t = nT$, then the transfer matrix P of the Markov renewal process $L_n = (X(nT), Y(nT), K(nT))$ is $\tilde{P}$ with state space $\{(x, y, k): k \geq 0, 0 \leq y \leq L, 1 \leq k \leq M + N\}$.

$$P = \begin{pmatrix} B_0^0 & B_0^1 & \cdots & B_0^{L+1} & \cdots \\ B_1^0 & B_1^0 & \cdots & B_1^{L+1} & \cdots \\ \vdots & \ddots & \ddots & \vdots & \vdots \\ & & B_L^L & B_L^{L+1} & \cdots \\ & & A_0 & A_1 & \end{pmatrix}$$
$$\xrightarrow{reorganization} \tilde{P} = \begin{pmatrix} B_0 & B_1 & B_2 & B_3 & \cdots \\ A_0 & A_1 & A_2 & A_3 & \cdots \\ & A_0 & A_1 & A_2 & \vdots \\ & & A_0 & A_1 & \cdots \\ & & & \ddots & \ddots \end{pmatrix} \qquad (1)$$

where, for $0 \leq i < L$, The dimension of matrix B_i^j is $(i+1)(M+N) * (i+1)(M+N)$ and The dimension of matrix A_i is $(L+1)(M+N) * (L+1)(M+N)$.

To compute the steady-state probability vector x of transfer matrix $\tilde{P}$ more quickly and easily, we use the formula provided in Reference [11,12].

$$x_i = \left[x_0 \bar{B}_k + \sum_{j=1}^{k-1} x_j \bar{A}_{k+1-j}\right](I - \bar{A}_1)^{-1} \quad k \geq 1 \qquad (2)$$

where $\bar{B}_k = B_k + \bar{B}_{k+1} G,\ \bar{A}_k = A_k + \bar{A}_{k+1} G$

Some of the key calculation processes are as follows, see reference [1] for detailed calculations.

i. Using $A = \pi; \pi e = e$, matrix $A = \sum_{i=0}^{\infty} A_i$ produces the steady-state probability vector π.
ii. Using the formula $\rho = \pi\beta;\ \beta = \sum_{i=0}^{\infty} i A_i e$ to calculate the traffic intensity ρ.
iii. The random matrix G is obtained by iterating $G_0 = A_0;\ G_n = \sum_{j=0}^{n} A_j G_{n-j}^{j},\ n > 0$.
iv. The steady state probability vector κ is obtained from the matrix K using $\kappa = K\kappa,\ \kappa e = e$

Using reference [13] to calculate x_0

$$x_0 = \frac{\kappa(1-\rho)}{1+\kappa[\sum_{j=0}^{\infty} j B_j e + (\sum_{j=0}^{\infty} B_j - I)(I - A + e\pi)^{-1}\beta]} \qquad (3)$$

To facilitate the computational analysis, it is necessary to sort the result by period as x_{ijs} in order to obtain the long-term change characteristics of the vehicle queue.

Let u_{ks} denote the steady-state distributed probability of vehicle queue length in a regular lane.

$$u_{ks} = (M+N)\, x_{(i+j)s};\ u_{hs} = (M+N)\, x_{js} \qquad (4)$$

Wit u_{ks}, we can obtain average queue length $E(L)$ and delay $E(W)$.

$$E(L) = \sum_{k=0}^{\infty} k u_{ks};\ E(W) = \frac{\sum_{k=0}^{\infty} k u_{ks}}{\lambda} \qquad (5)$$

Let L_m, L_{mr}, L_r denote the maximum number of queuing vehicles in the system versus the maximum number of queuing vehicles in the regular lane and the minimum number of queuing vehicles in the system, respectively

$$L_m = \sum_{k=0}^{\infty} k u_{k(M+N)};$$
$$L_{mr} = \sum_{h=0}^{\infty} h u_{h(M+N)}; \qquad (6)$$
$$L_r = \sum_{k=0}^{\infty} k u_{kM}$$

Let η denote the traffic efficiency of the intersection

$$\eta = \left(1 - \frac{L_r}{L_m + \lambda M T}\right) \times 100\% \qquad (7)$$

3.2 Vehicle Fuel Consumption Model

The operating modes of vehicles at signalized intersections include acceleration, deceleration, idling, and constant speed. As stated in reference [14], the total fuel consumption of vehicles passing through can be calculated using the following equation

$$FC = \sum_i^N (f_a^i\, t_a^i + f_d^i t_d^i + f_i^i t_i^i + f_u^i t_u^i) \qquad (8)$$

To incorporate the stochastic queuing model in this paper, the above equation can be adapted as follows

$$FC = \lambda \cdot [\bar{f_i} \cdot r + (\bar{f_a} + \bar{f_d}) \cdot E(W)] \qquad (9)$$

Firstly, regarding the congestion threshold L mentioned in the study. In this scenario, the number of vehicles stops would be the sum of vehicles arriving during the red-light period plus vehicles arriving during the green light period when the stranded vehicles clear out.

$$r_1 = \frac{L_m + min\,(\frac{L_{mr}T}{\lambda - T}, MT\lambda]}{C\lambda} \qquad (10)$$

Secondly, when the number of regular vehicles in queues reaches the congestion threshold L. the number of stops in a signal cycle is determined by the sum of vehicles entering the BRT lane, vehicles restarting in the general-purpose lane, and vehicles arriving during subsequent red-light periods.

$$N_a = max\big[\big((L_m - L_{mr}) - (L_r - L)\big), 0\big] + (L_r - L) + min\,[(L_r - L)\frac{\lambda T}{\lambda - T}, \frac{LT\lambda}{E(IS)}] \qquad (11)$$

Please note that all vehicles proceeding during the green light period do not leave the intersection before the start of the green light at the intersection.

$$N_b = (L_r - L) + min\left[\frac{L_{mr}\lambda T}{\lambda - T}, MT\lambda\right] + L_{mr}\lambda \qquad (12)$$

Let r_2 denote the stop rates per signal cycle, then we have the following equation

$$r_2 = \frac{N_a + N_b}{C\lambda} \qquad (13)$$

4. NUMERICAL SIMULATION AND ANALYSIS

In this section, a numerical simulation is performed to demonstrate the positive impact of implementing BRT shared lanes on reducing vehicle fuel consumption. The signal cycle at the intersection in the simulation was set to 80s and the green light duration to 30s.

4.1 Effects at Different Saturation Levels

This subsection examines the comparative effectiveness of employing shared BRT lanes versus the conventional strategy at various saturation levels. The saturation levels investigated in this study range from 0.1 to 0.9. It is worth noting that saturation plays a crucial role in influencing traffic efficiency. To simulate the traffic flow, conventional vehicles adhere to a Poisson process for their arrival patterns, whereas bus arrivals are modeled using a geometric distribution. The shared BRT lanes, as proposed in this paper, permit regular vehicles to utilize the BRT lanes exclusively when the regular lanes surpass a specific congestion threshold denoted as L. In practical terms, by implementing shared BRT lanes, the overall performance and traffic management can be significantly improved, particularly under conditions of high saturation. This innovative approach allows for enhanced utilization of existing road infrastructure and aids in alleviating congestion issues.

Figure 1 depicts a comparison of total fuel consumption between the utilization of shared BRT lanes and conventional lanes. The results are striking, revealing a substantial reduction in fuel consumption at signalized intersections when shared BRT lanes are employed. This reduction is particularly notable in situations where saturation levels are higher, indicating more severe traffic congestion. For instance, the implementation of shared BRT lanes can lead to a remarkable 64% decrease in total fuel consumption when congestion is at its peak. Moreover, As shown in Fig. 2, this approach significantly enhances intersection access efficiency. However, it is important to note that when traffic saturation is low and congestion is minimal, the fuel consumption data for both shared BRT lanes and conventional lanes are comparable. In such scenarios, where congestion is not a concern, the need for sharing BRT lanes may not be necessary.

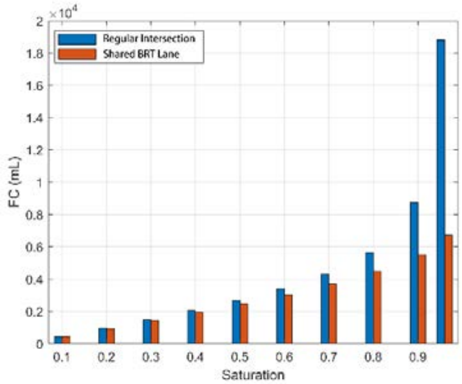

Fig. 2. Comparison of Fuel Consumption

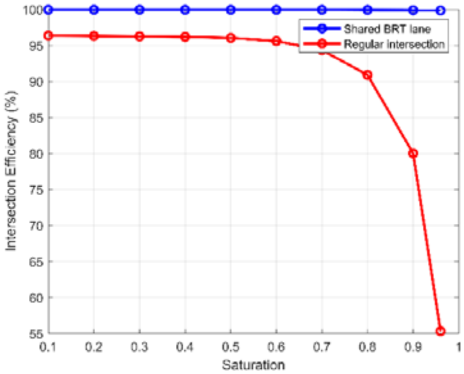

Fig. 3 Comparison of Intersection Efficiency

4.2 Impact of Shared BRT Lane Capacity

The capacity of the shared BRT lanes directly impacts the operational effectiveness of the strategy. If the capacity is excessive, it allows a large influx of regular vehicles into the BRT lanes, compromising the priority of BRT vehicles. On the other hand, insufficient capacity limits the effectiveness of the strategy. Therefore, it is crucial to carefully consider the effect of shared BRT lane capacity. Striking the right balance is essential to maintain the integrity of the BRT system while accommodating regular vehicles.

Fig. 4 illustrates the curves of total fuel consumption and average delay for different capacities. It is evident that the curve exhibits a decreasing trend initially, followed by an increase as the capacity incorrectly increases. The minimum point occurs at a capacity value of $L = 5$. This indicates that a higher capacity does not necessarily lead to increased effectiveness when implementing BRT shared lanes. Instead, proper capacity design is crucial for maximizing the benefits of shared BRT lanes.

Importantly, the curves reveal that irrespective of capacity, shared BRT lanes consistently result in lower total fuel consumption and vehicle delays compared to conventional strategies. This underscores the beneficial impact of shared BRT lanes. Furthermore, Fig. 5 demonstrates the correlation between the number of stops per vehicle and intersection efficiency, further supporting this finding.

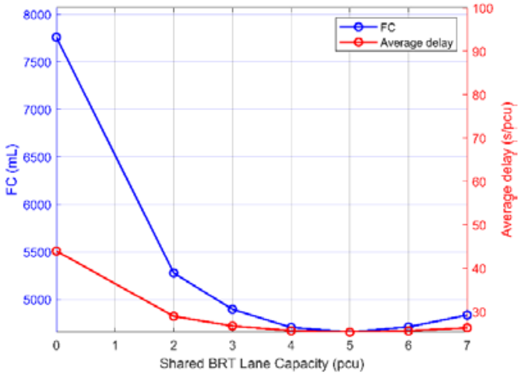

Fig. 4 Fuel Consumption and Delay

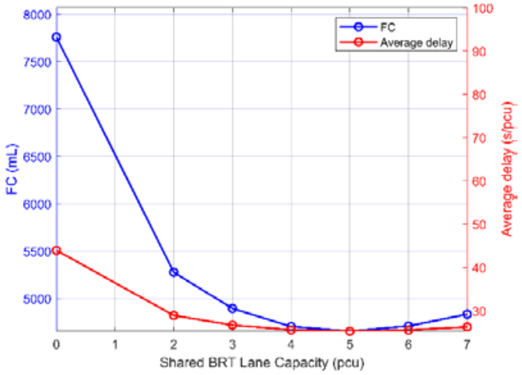

Fig. 5 Parking Rates and Intersection Efficiency

5. CONCLUSIONS

This paper proposes a shared BRT lane strategy as a potential solution to address environmental pollution caused by traffic congestion. The utilization of shared BRT lanes at intersections offers promising results in terms of reducing vehicle fuel consumption while maintaining intersection efficiency. The experimental findings indicate that shared BRT lanes can achieve a significant reduction in vehicle fuel consumption by up to 64% compared to conventional intersections. However, it is important to note that the modeling process in this research simplifies the arrival process of conventional vehicles and buses, and further refinement using real data is necessary to improve the accuracy of the model. Nonetheless, this study provides valuable insights into the sustainability of transportation and highlights the potential benefits of implementing shared BRT lane strategies to mitigate environmental pollution.

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DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

REFERENCE

[1] Hidalgo,D., & Gutiérrez, L. (2013). BRT and BHLS around the world: Explosive growth, large positive impacts and many issues outstanding. Research in Transportation Economics, 39(1), 8-13.

[2] Sakamoto, K., Abhayantha, C., & Kubota, H. (2007). Effectiveness of bus priority lane as countermeasure for congestion. Transportation research record, 2034(1), 103-111.

[3] Ma, C., & Xu, X. D. (2020). Providing spatial-temporal priority control strategy for BRT lanes: A simulation approach. Journal of Transportation Engineering, Part A: Systems, 146(7), 04020060.

[4] Abbasi, M., Hosseinlou, M. H., & JafarzadehFadaki, S. (2020). An investigation of Bus Rapid Transit System (BRT) based on economic and air pollution analysis (Tehran, Iran). Case Studies on Transport Policy, 8(2), 553-563.

[5] Scholl, L., Bouillon, C. P., Oviedo, D., Corsetto, L., & Jansson, M. (2016). Urban transport and poverty: Mobility and accessibility effects of IDB-supported BRT systems in Cali and Lima.

[6] Zhou, L., Wang, Y., & Liu, Y. (2017). Active signal priority control method for bus rapid transit based on Vehicle Infrastructure Integration. International Journal of Transportation Science and Technology, 6(2), 99-109.

[7] Al-Deek, H., Sandt, A., Alomari, A., & Hussain, O. (2017). A technical note on evaluating the effectiveness of bus rapid transit with transit signal priority. Journal of Intelligent Transportation Systems, 21(3), 227-238.

[8] Tamannaei, M., Fazeli, M., Chamani Foomani Dana, A., & Mansourianfar, H. (2019). Transit signal priority: proposing a novel algorithm to decrease delay and environmental impacts in BRT route intersections. International Journal of Transportation Engineering, 7(2), 153-169.

[9] Wang, Y., Wang, Z., Li, Z., Staley, S. R., Moore, A. T., & Gao, Y. (2013). Study of modal shifts to bus rapid transit in Chinese cities. journal of transportation engineering, 139(5), 515-523.

[10] Hensher, D. A., & Golob, T. F. (2008). Bus rapid transit systems: a comparative assessment. Transportation, 35, 501-518.

[11] Hu, X. N., Tang, L. C., & Ong, H. L. (1997). AM/Dx/1 vacation queue model for a signalized intersection. Computers & industrial engineering, 33(3-4), 801-804.

[12] Ramaswami, V. (1988). A stable recursion for the steady state vector in Markov chains of M/G/1 type. *Stochastic Models*, *4*(1), 183-188.

[13] Helmut, S. (1990). On Ramaswami's algorithm for the computation of the steady state vector in Markov chains of M/G/1-type. *Stochastic Models*, *6*(3), 541-550.

Wu, L., Ci, Y., Wang, Y., & Chen, P. (2020).

[14] Fuel consumption at the oversaturated signalized intersection considering queue effects: a case study in Harbin, China. Energy, 192, 116654.