Simulation-Based Analysis of Bus Dedicated Lane Efficiency for Urban Traffic Management

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Keywords: Street, Traffic Lane, Dedicated Bus Lane, Automobiles, Traffic Signal, Traffic Congestion, Road, Delay.

Abstract: This study proposes a simulation-based approach aimed at increasing the operational speed of public transport and reducing delays at signalized intersections. As study corridors, Amir Temur Street in Tashkent, where a dedicated bus lane is implemented, and Parkent Street, where buses operate in mixed traffic, were selected for a comparative corridor analysis. The corridors were compared using traffic-flow speed characteristics, vehicle-delay indicators, and queue-related parameters; however, the comparison should be interpreted as an indicative real-world corridor assessment rather than a fully controlled causal experiment. The field observations showed that the average bus delay at the studied intersection in mixed traffic was 242.3 s, whereas on the corridor with a dedicated bus lane it was 113.67 s, giving a difference of 128.63 s. To interpret these operating conditions analytically, a queue-based mathematical model was developed and implemented in the SUMO software environment for further simulation and analysis. The agreement between the model outputs and the field observations was additionally checked using Fisher's criterion at the 99% confidence level. The proposed approach can be applied to evaluate congestion levels on major urban streets and to support the operational planning of public transport movement under different traffic conditions.

1 INTRODUCTION

High traffic volumes on urban streets are regulated by traffic signals or road signs. Consequently, motor vehicles are required to stop for certain periods, which results in varying levels of congestion within the street and roadway network [1], [2]. Traffic congestion, including the delays experienced by vehicles at intersections, was examined using the major urban corridors of Tashkent-Amir Temur and Parkent streets-as case studies.

Based on the results obtained from these research objects, the parameters of dedicated lanes for urban public transport and the operational characteristics of vehicles were determined. The study focuses on the implementation procedures of dedicated traffic lanes for buses and investigates their effects on the operational performance of public transport vehicles.

Building on models from Russia (A.A. Antonova and A.Yu. Mikhailov), as well as frameworks from the United States and South Korea, criteria for allocating priority lanes for buses based on the number of vehicles and public transport units were analyzed. These criteria were then applied to streets in Irkutsk [3]. Methodological approaches for assessing the feasibility of allocating dedicated lanes to public transport have also been developed in previous transport-planning research [4]. The study proposed standards for allocating priority lanes for public transport. Unlike the research by Antonova and Mikhailov, which considered only the number of buses and passengers passing within a single hour, the present study developed criteria that account for the delays incurred by buses due to congestion. Based on these criteria, a mathematical model was created and simulated in the SUMO software.

1.1 Scientific Novelty

The scientific novelty of this study lies in the following contributions:

- a comparative corridor framework for evaluating bus operation under mixed-traffic and dedicated-lane conditions using intersection delay as the main performance indicator;
- a queue-based analytical model implemented in SUMO to estimate lane occupancy, excess waiting time, and the number of vehicles unable to clear the intersection during the green phase;
- an empirical validation of the modelling results using field data from urban corridors in Tashkent.

1.2 Practical Applications

The experiment was conducted both visually and using automated measurement methods. To ensure the reliability of the results, measurements were taken for no fewer than 150 observations. Street and roadway parameters were measured using standard measuring tools and GIS software, which increased the accuracy and reliability of the data. The time vehicles were delayed in congestion was directly recorded using a standard stopwatch during experimental trials.

2 METHODS

During the research process, a combination of experimental observation, monitoring, mathematical analysis, synthesis of key components, modeling, and systematic and theoretical analysis methods were applied, yielding the following outcomes:

- Identification of the formation patterns of traffic congestion for vehicles.
- Evaluation of the impact of geometric parameters of traffic lanes on vehicle speed.
- Development of a methodology for implementing dedicated lanes for buses under various urban traffic conditions.
- Construction and simulation of a mathematical model that accounts for the formation of congestion among vehicles.

2.1 Study Corridors and Comparability Conditions

The study was conducted on two major urban corridors in Tashkent: Amir Temur Street, where a dedicated lane for buses is implemented, and Parkent Street, where buses operate in mixed traffic flow. The comparison was performed at signalized intersections under high-demand urban traffic conditions.

The selected corridors were compared using geometric, operational, and traffic-performance indicators, including the number of traffic lanes, street width, signal control, traffic composition, and bus operating conditions. At the same time, because the corridors are not perfectly identical in all infrastructure and control characteristics, the comparison should be interpreted as an indicative real-world corridor assessment rather than as a strictly controlled causal experiment.

Therefore, the purpose of the comparison was to identify whether the observed operating conditions on the corridor with a dedicated bus lane are associated with lower bus delay and more stable traffic performance than on the corridor with mixed traffic operation. The principal geometric, operational, and traffic-performance characteristics of the two study corridors are summarized in Table 1.

3 RESEARCH RESULTS

Amir Temur Street, which includes dedicated lanes for bus movement, has a total street-road network length of 45.4 km. The street comprises 8 traffic lanes, with an average street width of 30 meters. At the intersection of Amir Temur and Shahriston streets, the traffic signal cycle is set as follows: red light - 35 seconds, green light - 45 seconds, and yellow light - 3 seconds. The observed distribution of traffic-flow speeds on Amir Temur Street is presented in Figure 1.

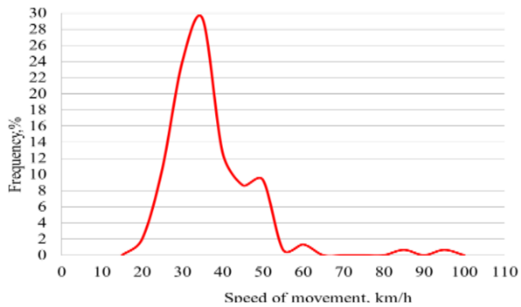

Figure 1: Distribution curve of traffic flow speed on Amir Temur Street.

Table 1: Main characteristics of the compared study corridors.

Parameter	Amir Temur Street	Parkent Street
Observed intersection	Amir Temur-Shahriston	Parkent-Parkent 4-lane
Bus operating condition	Dedicated bus lane	Mixed traffic
Traffic control	Signalized intersection	Signalized intersection
Roadway configuration	8 traffic lanes; average street width 30 m	4-lane intersection; mixed-flow corridor
Signal timing at observed intersection	Red 35 / Green 45 / Yellow 3	Not reported in the current manuscript
Minimum number of observations	≥150	≥150
Main comparison indicator	Bus delay at intersection	Bus delay at intersection
Average bus delay, s	113.67	242.3

Note: The compared corridors were analyzed under real urban operating conditions. For Parkent Street, some geometric and signal-control parameters were not explicitly reported in the current manuscript; therefore, only the parameters directly supported by the presented field results are included in the table.

The results of the experimental study conducted on Amir Temur Street, which features dedicated lanes for bus movement [5], indicate that the maximum traffic flow speed on the street reached 95 km/h, representing 0.5% of the total traffic flow. Similarly, a speed of 85 km/h was observed for another 0.5% of vehicles.

The variation range of vehicle speeds on Amir Temur Street was calculated as follows:

$$R = R_{max} - R_{min} = 95 - 15 = 80 km/h.$$

This relatively large value indicates significant instability in vehicle speeds and demonstrates that traffic flow is not uniform along the corridor. The cumulative distribution of traffic-flow speeds on Amir Temur Street is illustrated in Figure 2.

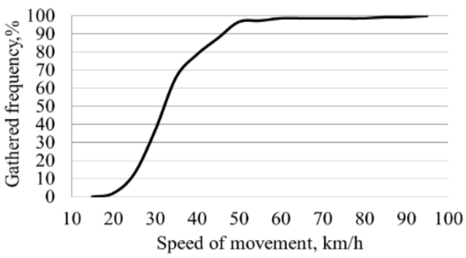

Figure 2: Aggregated distribution curve of traffic flow on Amir Temur Street.

On Amir Temur Street, 85% of vehicles traveling along the studied sections achieved a speed of 44 km/h. The normalized speed distribution according to vehicle type is shown in Figure 3. This indicates that, within the urban area, 85% of vehicles on the sections traveled at speeds 16 km/h below the maximum achievable speed. One plausible explanation for this reduction is the presence of dedicated lanes for bus movement, which may redistribute part of the traffic flow among the remaining lanes and thereby influence the speed distribution of vehicles along the corridor.

The cumulative speed analysis showed clear differences among vehicle types. For buses, the 15th, 50th, 85th, and 95th percentile speeds were 28, 29, 38, and 41 km/h, respectively. For trucks, the corresponding values were 29, 34, 38, and 39 km/h, while for passenger cars they were 35, 40, 51, and 54 km/h. These results confirm that operational speeds vary substantially across vehicle categories, with passenger cars showing the highest speed characteristics and buses the lowest within the observed traffic flow.

The experimental results indicate that the speed distributions differ significantly among vehicle types. The modal speed for buses was found to be 35 km/h, while for trucks it was 38 km/h, and for passenger cars 40 km/h. The cumulative speed distributions for the different vehicle categories are presented in Figure 4. These findings highlight the considerable variation in movement speeds among different categories of vehicles. Notably, the modal speed of buses is lower than that of trucks by 3 km/h, reflecting the operating characteristics observed on this corridor, including the presence of dedicated bus-lane organization and the overall traffic-flow structure.

The results of vehicle delays at the traffic signal located at the intersection of Amir Temur and Shahriston streets indicate that the traffic flow experiences multiple peaks in stoppage duration. Specifically, seven distinct peaks were identified: 110 seconds at a density of 4%, 225 seconds at 6.2%, 240 seconds at 6%, 255 seconds at 6%, 280 seconds at 5.4%, 295 seconds at 6%, and 335 seconds at 2.7% density. These findings demonstrate that the delays of vehicles at the intersection are highly unevenly distributed. Therefore, further analysis of intersection delays by traffic-flow composition is appropriate (see Fig. 5).

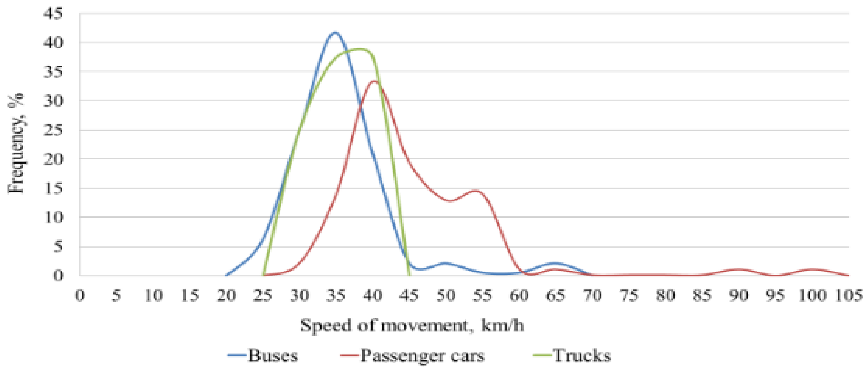

Figure 3. Normalized distribution of traffic flow by vehicle type on Amir Temur Street.

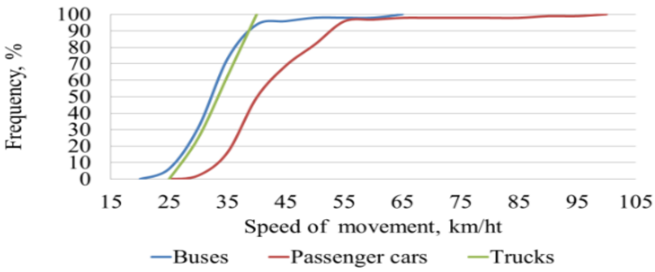

Figure 4: Cumulative distribution curve of traffic flow by vehicle type on Amir Temur Street.

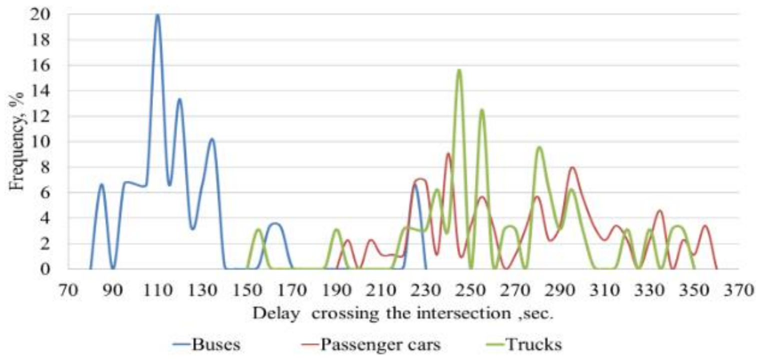

Figure 5: Distribution curve of vehicle delays at the Amir Temur-Shahriston intersection by vehicle type.

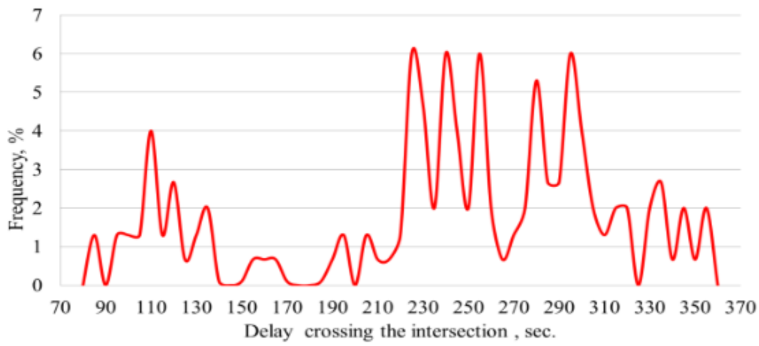

Figure 6: Distribution curve of vehicle delays at the Amir Temur-Shahriston intersection.

As shown in Figure 5, the maximum delay experienced by buses at the intersection occurs at a density of 20%, amounting to 110 seconds. Additional observed delays include 85 seconds at 6.5% density, 120 seconds at 13.5% density, 135 seconds at 10% density, 165 seconds at 3.5% density, and the longest delay of 225 seconds at 6.5% density. The average delay for buses at this intersection was calculated as 113.67 seconds. For passenger cars, the maximum delays were observed at 240 seconds at 9% density and 295 seconds at 8% density. Additional delays of 225 seconds at 7% density and 295 seconds at 8% density were also recorded. The mean delay for passenger cars at the intersection was 270.93 seconds. For trucks, the maximum delay at the intersection was 245 seconds at 15.5% density, 255 seconds at 12.5% density, and 345 seconds at 3.4% density. These results demonstrate significant variation in intersection delays depending on vehicle type and traffic density, highlighting the uneven distribution of stoppage times in mixed urban traffic flows. The traffic-flow speed distribution observed on Parkent Street is presented in Figure 7.

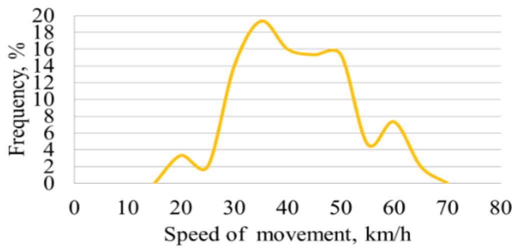

Figure 7: Distribution curve of traffic flow speeds on Parkent Street.

The results of the experimental study conducted on Parkent Street, where traffic operates under mixed flow conditions, indicate that the modal speed of the traffic flow is 35 km/h at a density of 19.3%. The distribution curve demonstrates that vehicle speeds are unevenly distributed, reflecting the dynamics of individual vehicles within the flow.

The variation range of vehicle speeds on Parkent Street is calculated as:

$$R = R_{max} - R_{min} = 70 - 15 = 55 km/h.$$

The vehicle type and traffic condition corresponding to the 70 km/h upper bound on Parkent Street are not specified in the present dataset; this value appears to reflect an occasional high-speed outlier rather than a typical operating speed, since the 95th-percentile speeds reported by vehicle type for this corridor (61 km/h for passenger cars, 49 km/h for minibuses) are substantially lower. Likewise, the lower maximum speed on Parkent Street compared with Amir Temur Street (70 vs. 95 km/h) is consistent with Parkent Street's mixed-traffic, non-dedicated-lane operation, but this explanation is offered here as an interpretive note rather than as a statistically tested comparison.

This relatively large range indicates significant instability in vehicle speeds and low uniformity in traffic flow.

Furthermore, 85% of vehicles traveling along the studied sections of Parkent Street achieved speeds of up to 50 km/h. The cumulative traffic-flow speed distribution for Parkent Street is illustrated in Figure 8. This variability may be associated with the heterogeneous dynamic characteristics of the vehicles within the mixed traffic flow.

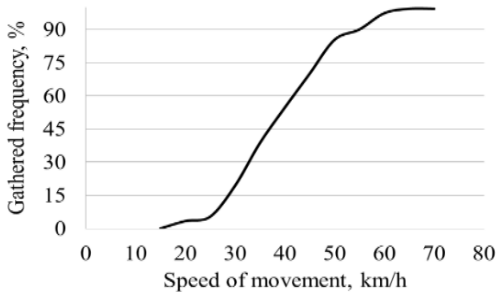

Figure 8: Cumulative distribution curve of traffic flow on Parkent Street.

Therefore, studying the traffic flow according to the composition of vehicle types provides a more appropriate approach for analyzing vehicle movement along the corridor (see Fig. 9).

The results of the experimental study indicate that the speed distributions differ significantly among vehicle types. The modal speed for buses is 35 km/h, for trucks it is 34 km/h, for passenger cars 45 km/h, and for minibuses 42 km/h. The cumulative distribution of speeds along the studied section shows that, for buses, the 15th percentile speed is 27 km/h, the 50th percentile (median) speed is 33 km/h, the 85th percentile speed is 38 km/h, and the 95th percentile speed is 41 km/h. For trucks, the 15th percentile speed is 25 km/h, the 50th percentile speed is 33 km/h, the 85th percentile speed is 47 km/h, and the 95th percentile speed is 50 km/h. These results highlight the considerable variation in speeds between different vehicle types within the mixed traffic flow and provide additional insight into the traffic dynamics observed along Parkent Street. Lane-changing behaviour may additionally affect traffic-flow velocity and contribute to speed variability in mixed traffic environments [6]. The cumulative speed distributions by vehicle type on Parkent Street are shown in Figure 10.

For passenger cars, the 15th percentile speed is 37 km/h, the 50th percentile (median) speed is 45 km/h, the 85th percentile speed is 57 km/h, and the 95th percentile speed is 61 km/h. For minibuses, the 15th percentile speed is 37 km/h, the 50th percentile speed is 41 km/h, the 85th percentile speed is 47 km/h, and the 95th percentile speed is 49 km/h. The distribution of vehicle delays at the Parkent-Parkent four-lane intersection is presented in Figure 11. These observations indicate that trucks exhibit lower dynamic performance characteristics compared to other vehicle types, which contributes to the observed speed distributions in the mixed traffic flow.

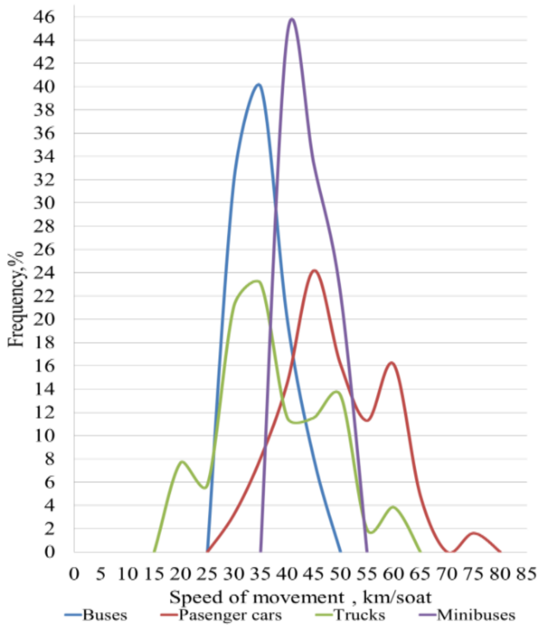

Figure 9: Distribution curve of traffic flow by vehicle type on Parkent Street.

The results of vehicle delays at the traffic signal located at the Parkent-Parkent 4-lane intersection indicate that, similar to the patterns observed in Figure 6, the overall traffic flow exhibits two distinct peaks in stoppage durations. The delays of vehicles range between 210 and 290 seconds, with the highest frequency occurring at 245 seconds for a density of 12.1% and at 274 seconds for a density of 7.5%. The distribution curve shows that vehicle delays at the intersection are highly uneven. Importantly, the maximum observed delays are significantly higher than the mean delay values. Therefore, it is necessary to analyze intersection delays according to the composition of the traffic flow (see Fig. 12).

As shown in Figure 12, the maximum delays experienced by buses at the intersection occur at a density of 27.8%, amounting to 244 seconds. Additional observed delays include 255 seconds at 11.2% density and 270 seconds at 2.3% density. The average delay for buses at this intersection was calculated as 242.3 seconds. For passenger cars, the maximum delay was observed at 259 seconds at 12.5% density, with an average delay of 241.9 seconds. For trucks, the maximum delay at the intersection was 270 seconds, occurring at a density of 19.5%. These results indicate that vehicle delays at the intersection are substantial and vary significantly with traffic density and vehicle type, highlighting the uneven distribution of stoppage times in mixed urban traffic flows.

A direct comparison of the average bus delay values obtained for the two corridors shows a substantial operational difference. On Amir Temur Street, where buses operate on a dedicated lane, the average intersection delay of buses was 113.67 s. On Parkent Street, where buses move in mixed traffic, the corresponding value was 242.3 s. Thus, the observed difference amounted to 128.63 s, suggesting that the corridor with dedicated-lane priority was associated with more favorable operating conditions for buses under the studied real-world traffic conditions. The influence of mixed-traffic conditions on public transport operating performance is also consistent with previous modelling studies of the optimal number and operation of public transport vehicles [7].

4 MATHEMATICAL MODEL

4.1 Simulation Model

Figure 13 illustrates the organization of vehicles and buses within the overall traffic flow and within the dedicated bus lanes.

Figure 14 presents the schematic of the simulation model created in the SUMO software for vehicles operating in mixed traffic flow.

4.2 Digital Traffic Modelling

Vehicle Arrival Processю Vehicle arrivals are assumed to follow a Poisson distribution, which is commonly used to represent random traffic arrivals.

$$P(k) = \frac{\alpha^k e^{-\alpha}}{k!}. \quad (1)$$

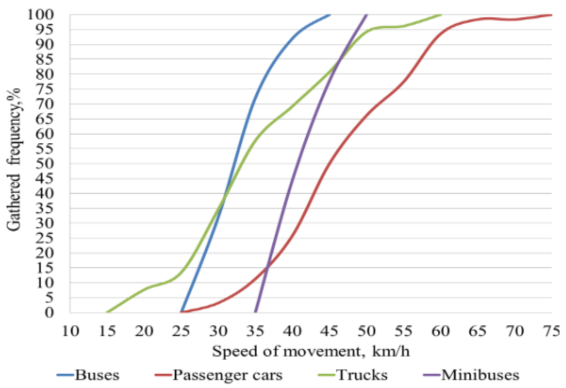

Figure 10: Cumulative distribution curve of traffic flow by vehicle type on Parkent Street.

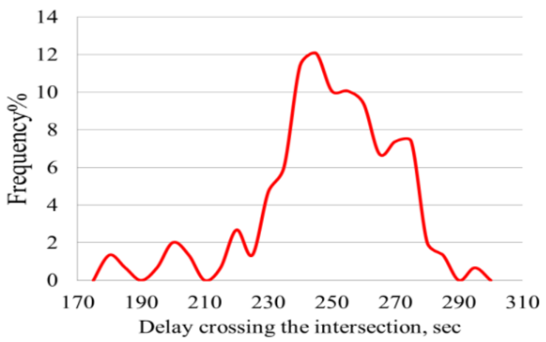

Figure 11: Distribution of vehicle delays at the Parkent-Parkent 4-lane intersection.

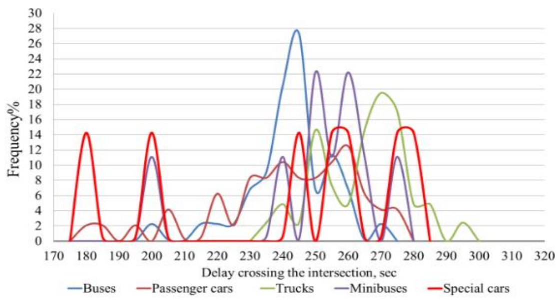

Figure 12: Distribution of vehicle delays at the Parkent-Parkent 4-lane intersection.

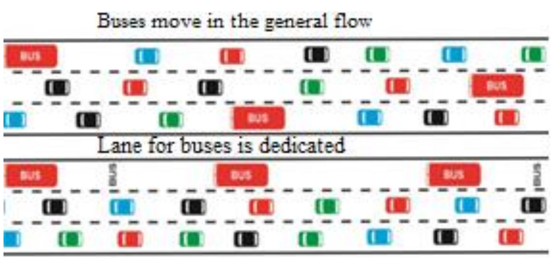

Figure 13: Bus traffic patterns in the general flow and on the bus lane on 3 lanes road.

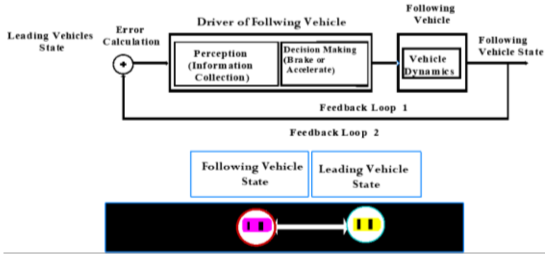

Figure 14: Vehicle flow model diagram made in SUMO software.

Queue Formation. If all service channels are occupied, newly arriving vehicles form a queue. The expected queue length can be estimated using:

$$L_q = \frac{p^{n+1}}{n!(1-\rho)^2} P_0. \qquad (2)$$

Vehicles approaching the intersection do not face any spatial constraints for stopping; each vehicle waits its turn and begins to move when the traffic signal displays a permissive green phase, stopping when the red phase is active [8]-[10]. A mathematical model was developed for the scenario in which the green signal lasts 30 seconds. For analytical generalization, the queueing model was first formulated for a standardized green-phase duration of 30 s, representing a typical service interval for one signal phase. The empirical results obtained at the Amir Temur-Shahriston intersection were then used to compare the model behavior with field observations under the actual signal settings. Therefore, the analytical model should be interpreted as a generalized service-phase representation, whereas the field study reflects the real operational signal cycle.

If we theoretically determine the probability of channel occupancy for the lane dedicated to directional buses [11], [12], assuming an arrival rate of 14 vehicles per minute to the bus-only lane,

$$\lambda = \frac{14}{1} \quad \left[\frac{1}{min}\right].$$

Service parameters for the traffic flow in the dedicated bus lane:

$$\frac{1}{\mu} = 4\ sek = \frac{4}{60} min = \frac{1}{15}\left[\frac{1}{min}\right],$$

$$\mu = 15 \left[\frac{1}{min}\right].$$

For the general traffic flow:

$$\alpha = \frac{\lambda}{\mu} = \frac{14}{15} = 0{,}93;$$

$$\varkappa_1 = \frac{\lambda}{n\mu} = \frac{14}{1 \cdot 15} = \frac{14}{15} = 0{,}93;$$

$$\frac{1}{\nu} = \frac{30}{60} min;$$
$$\nu = 2\left[\frac{1}{min}\right];$$
$$\delta = \frac{n \cdot \mu}{\nu} = \frac{1 \cdot 15}{2} = 7{,}5 \approx 8;$$
$$\gamma = \frac{\lambda}{\nu} = \frac{14}{2} = 7.$$

Probability of lane occupancy:

$$\overline{k_{14}} = \frac{\alpha R(n-1,\alpha) + nP(n,\alpha)\ \dfrac{R(m+\delta_1,\gamma_1) - R(\delta,\gamma)}{P(\delta,\gamma)}}{R\,(n,\alpha) + P(n,\alpha)\ \dfrac{R(m+\delta,\gamma) - R(\delta,\gamma)}{P(\delta,\gamma)}},$$

$$\overline{k_{14}} = \frac{1\,R(0,1) + 1\,P(1,1)\ \dfrac{R(\infty+8,7) - R(8,7)}{P(8,7)}}{R\,(1,1) + P(1,1)\dfrac{R(\infty+8,7) - R(8,7)}{P(8,7)}}$$
$$= \frac{0{,}36788 + 0{,}36788 \cdot \dfrac{1 - 0{,}72909}{0{,}13038}}{0{,}73576 + 0{,}36788 \cdot \dfrac{1 - 0{,}72909}{0{,}13038}}$$
$$== \frac{0{,}36788 + 0{,}764399223}{0{,}73576 + 0{,}764399223}$$
$$= \frac{1{,}13227922}{1{,}50015922} = 0{,}754772697.$$

Here $k_{14} \leq 1$, becuse there is 1 service line. $k_{14} = 0{,}754772697$

During the service period, a portion of vehicles that cannot pass the intersection forms a queue at the intersection. As additional vehicles arrive, they stop behind the queued vehicles, resulting in the accumulation of vehicles in front of the intersection [9]. This S_0 - process repeats and can be represented as a transition from the first state to the second state, as expressed in (4).

$$\boxed{S_0} \underset{\mu}{\overset{N}{\rightleftarrows}} \boxed{S_1} \underset{2\mu}{\overset{N}{\rightleftarrows}} \boxed{S_2} \underset{3\mu}{\overset{N}{\rightleftarrows}} \dots \underset{k\mu}{\overset{N}{\rightleftarrows}} \boxed{S_k} \rightleftarrows \dots \underset{n\mu}{\overset{N}{\rightleftarrows}} \boxed{S_n} \underset{n\mu+\nu}{\overset{N}{\rightleftarrows}} \boxed{S_{n+1}} \rightleftarrows \dots \rightleftarrows \boxed{S_{n+\nu}} \rightleftarrows \cdots; \quad (4)$$

The calculated traffic-flow parameters for the three service lanes are summarized in Table 2.

- $P_{x\,k\,e}$ - Service probability;
- $\bar{t}_{\ i\,q\,v}$ - Average downtime of the lane;
- λ -Number of vehicles passing through the intersection;
- $\bar{\kappa}$ –Probability of lanes occupancy;
- $\bar{t}_{\ iqv}$- Excess waiting time at the intersection;
- μ –Service time per vehicle;
- $\alpha, \gamma, \delta, \nu$ – Computational coefficients;
- $\sum_{s=1}^{m} M$ –Number of vehicles unable to pass intersection during the green signal for model;
- $\sum_{s=1}^{m} E$ –Number of vehicles unable to pass intersection during the green signal for experiment;
- n –Number of traffic lanes.

For readers unfamiliar with the underlying queueing formalism, R(n,α) and P(n,α) in the occupancy-probability formula (e.g., in the computation of $\bar{k}_{14}$) denote, respectively, the Erlang-type partial-sum (loss) function and the Poisson probability mass function evaluated at n servers/arrivals under traffic intensity α; these are standard building blocks of Erlang loss/queuing formulas used to compute steady-state occupancy and blocking probabilities, and are applied here in their conventional form rather than as a bespoke construct of this study.

To evaluate the agreement between the analytical model and field observations, Fisher's variance ratio test was applied.

Null hypothesis H0: the variances of the model results and the experimental observations do not differ significantly.

Alternative hypothesis H1: the variances of the model results and the experimental observations differ significantly.

The compared samples consisted of the numbers of vehicles unable to clear the intersection during the green phase, obtained from the analytical model and from field observation. The Fisher-test calculations used to verify agreement between the analytical and experimental results are presented in Table 3.

Table 2: Mathematical computation of the traffic flow entering the three service lanes.

λ	$\sum_{s=1}^{m} S$	$\bar{\kappa}$	$P_{x\,k\,e}$	$\sum_{s=1}^{m} E$	$\bar{t}_{\ i\,q\,v}$ [sek]	$\mu\left[\frac{1}{min}\right]$	α	$\nu\left[\frac{1}{min}\right]$	γ	δ
5	0,653	0,306	0,769	0	9,074	15	0,3	2	3	8
6	0,653	0,370	0,714	0	6,805	15	0,4	2	3	8
8	1,129	0,424	0,117	0	5,441	15	0,5	2	4	8
10	1,870	0,588	0,588	2	2,797	15	0,7	2	5	8
12	3,041	0,665	0,555	3	2,017	15	0,8	2	6	8
14	4,922	0,755	0,5	5	1,299	15	1	2	7	8
16	8	0,797	0,5	7	1,020	15	1	2	8	8

Table 3: Verifying the reliability of the results obtained according to Fisher's theory with 99% confidence.

№	λ	$\sum_{s=1}^{m} S$	$\sum_{s=1}^{m} E$	$(x_{1i}-x_1)$	$(x_{2i}-x_2)$	$(x_{1i}-x_1)^2$	$(x_{2i}-x_2)^2$
1	5	0.653	0	2.242	2.248	5.0265	5.8952
2	6	0.653	0	2.242	2.248	5.0265	5.8952
3	8	1.129	0	1.766	2.248	3.1187	5.8952
4	10	1.870	2	1.025	0.428	1.0506	0.1832
5	12	3.041	3	-0.146	-0.572	0.2131	0.3272
6	14	4.922	5	-2.027	-2.572	4.1087	6.411
7	16	8	7	-5.105	-4.572	26.061	20.903
		2.895‘	2.428			44.6051	45.5102

The sample variances of the analytical and empirical datasets were calculated as:

$$S_{1x}^{\ 2} = \frac{\sum(x_{1i}-x_1)^2}{n-1} = \frac{44{,}6051}{7-1} = 7.4342;$$

$$S_{2x}^{\ 2} = \frac{\sum(x_{2i}-x_2)^2}{n-1} = \frac{45{,}5012}{7-1} = 7.58503,$$

respectively. Since $S_{2x}^{\ 2} > S_{1x}^{\ 2}$, the empirical Fisher ratio was calculated as

$$F_{emp} = \frac{S_{2x}^{\ 2}}{S_{1x}^{\ 2}} = \frac{7.58503}{7.4342} = 1.0203.$$

Because $F_{emp} < F_{crit} = 13.27$ at the adopted confidence level, the null hypothesis was not rejected. This indicates that the variability of the analytical and experimental results is statistically consistent within the adopted confidence level. The degrees of freedom underlying this critical value were not explicitly stated in the original computation; with $n_1 = n_2 = 6$ observation groups ($df_1 = df_2 = 5$) at $\alpha = 0.01$ the tabulated critical value is approximately 8.47 rather than 13.27, so the degrees of freedom actually used to obtain F_crit = 13.27 should be reported explicitly in a future revision to allow independent verification of this test.

5 CONCLUSIONS

This study presented an experimental and simulation-based investigation of vehicle speeds, delays, and congestion patterns on two urban corridors in Tashkent, comparing mixed-traffic operation with dedicated bus-lane operation. Field observations showed that the average bus delay at the studied intersection was 242.3 s on Parkent Street, where buses operate in mixed traffic, and 113.67 s on Amir Temur Street, where a dedicated bus lane is implemented. The observed reduction of 128.63 s indicates substantially more favorable operating conditions for buses under dedicated-lane operation.

In addition to the field observations, a queue-based analytical model was developed to estimate lane occupancy, excess waiting time, and the number of vehicles unable to clear the intersection during the green phase. The model was implemented in the SUMO simulation environment, enabling comparison between analytical estimates and observed traffic performance. Statistical verification using Fisher's criterion demonstrated good agreement between the analytical results and field observations, supporting the applicability of the proposed approach for operational traffic analysis.

Although the findings are consistent with the operational benefits of dedicated bus lanes, they should be interpreted as evidence from a real-world corridor comparison rather than as results of a strictly controlled causal experiment. Further studies involving corridors with more closely matched geometric characteristics, signal-control parameters, and traffic-demand conditions would strengthen causal inference.

The proposed methodology has practical value for urban traffic management and public transport planning. The identified delay patterns can serve as operational indicators of congestion at signalized intersections, while the queue-based model provides a useful tool for estimating lane utilization, vehicle queues, and waiting times under different traffic conditions. Its integration into the SUMO environment enables scenario-based evaluation of public transport priority measures and supports evidence-based traffic management decisions. Overall, the combination of field measurements, analytical modeling, and statistical validation confirms the reliability of the proposed framework and its suitability for comparative operational analysis and further development of urban traffic-priority strategies.

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