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Original Article

Comparative Analysis of Queueing Performance Measures at different BRTS Stations in Ahmedabad

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Abstract *- This study is based on a queueing analysis of BRTS stations across Ahmedabad, Gujarat. Three stations have been chosen, and observations are performed to collect primary data. A two-node queueing model is suitable for each station, with the first node serving as the ticket window and the second as the bus waiting area. Furthermore, there are variations in the number of buses that arrive at each stop. In this study, Numerical analysis is performed for performance measures such as waiting line, number of people in the system, Average waiting time, Utilization rate, etc., of the queueing model. By identifying these critical pressure points, the study can suggest targeted interventions, such as optimizing station design, revising bus schedules, or implementing advanced ticketing technologies to reduce congestion and streamline passenger flow.*

These data-driven interventions, such as route scheduling, spatial load balancing and flexible resource allocation, collectively offer a cost-effective framework for congestion mitigation in BRTS systems with minimal infrastructure modifications. Our findings provide actionable insights for transit authorities aiming to enhance operational efficiency while maintaining service quality in high-demand urban corridors.

Keywords *- Queueing analysis, Two-node queueing model, Performance measure.*

1. Introduction

Janmarg, commonly known as Ahmedabad BRTS, is a bus rapid transit system in Ahmedabad, Gujarat, India, established in 2009. Ahmedabad Janmarg Ltd operates 160 km of routes with 380 buses, serving approximately 2.20 lakh passengers daily [8]. Since its inception, the BRTS has played a crucial role in thousands of passengers' everyday journeys, providing an affordable and environmentally friendly alternative for private vehicle and bus transportation. However, the system's effectiveness depends not only on its infrastructure and service frequency but also on the operational efficiency of individual stations. As urban populations rise and traffic congestion worsens, the functioning of BRTS stations becomes more crucial in providing a smooth flow of passengers and reducing delays. The efficiency of these stations directly impacts passenger satisfaction, reliability, and overall level of service. Therefore, understanding and improving the performance of BRTS stations is essential to maintaining the system's effectiveness.

Patel and Gor[8] (2024) conducted a comprehensive study examining passenger perceptions of BRTS service quality in Ahmedabad through factor analysis and discriminant analysis techniques. Their research identified crowding as a critical determinant of user dissatisfaction, with two primary indications: overcrowded buses and congested stations. These findings highlighted that variables such as excessive queues at ticket windows, peak-hour station crowding, and insufficient seat availability significantly negatively impact passenger satisfaction.

Queueing theory, a mathematical study of waiting lines, offers a robust framework for analysing the performance of service systems, including public transportation hubs like BRTS stations. By examining key queueing performance measures such as average waiting time, queue length and system utilization, we can gain insights into the operational efficiency of different stations. Hence, the results of this study will offer major insights that enhance the efficiency of BRTS functions in Ahmedabad.

One of the primary outcomes of this analysis will be the identification of bottlenecks that cause excessive waiting times and long queues, which are common sources of frustration for passengers. For instance, high passenger volumes during peak hours can lead to overcrowding, extended boarding times and delays, ultimately compromising the system's reliability. The study also provides a comparative analysis of the performance and utilization rates of various stations. Additionally, it aims to identify the underlying factor (bus) contributing to overcrowding at bus stations.

In this study, three BRTS stations - station X, station Y and station Z were selected for analysis. Although the operational functioning of these stations is identical, the buses arriving at each station differ—the data below details each bus that visited the respective station during the observation period.

Table 1.1.1. Bus arrival list at BRTS Station

Station	Bus number- Route name
Station X	14D - Naroda Gam to Sanand Circle
	5D – Hanspura Ring Road to Vasna
	5U- Vasna to Hanspura Ring Road
	8D – Naroda Gam to Isckon Cross Road
Station Y	8U – Isckon Cross Road to Naroda Gam
	9U – Gota Vasant Nagar Township to Maninagar
	8D - Naroda Gam to Isckon Cross Road
	9D - Maninagar to Gota Vasant Nagar Township
	11U – L.D. Engineering College to S.P. Ring Road Approach
	4D – L.D. Engineering College to Zundal Circle
Station Z	12D – CTM Cross Road to Chandkheda Gam
	3D – Maninagar to Chankheda Gam
	9D - Maninagar to Gota Vasant Nagar Township
	4D – L.D. Engineering College to Zundal Circle
	4U - Zundal Circle to L.D. Engineering College
	9U – Gota Vasant Nagar Township to Maninagar
	1U – Guma Gam to Maninagar
	3U – RTO Circle to Maninagar
	17D – Nehrunagar to South Bopal
	16D – Nehrunagar to Sanand Circle
	8D - Naroda Gam to Isckon Cross Road
	1D - Maninagar to Guma Gam
	8U – Isckon Cross Road to Naroda Gam
	12U – Chankheda Gam to CTM Cross Road
	101U – RTO Circle to RTO Circle

2. Literature Review

Widanapathiranage[9](2015) examined a bus waiting line at a bus station. They used microscopic simulation to examine and analyse the station's operational characteristics under near steady-state circumstances, including output variables such as capacity, degree of saturation, and queuing. In the first of two stages, a mathematical model for the potential capacity of all stopping buses with bus-to-bus interference was created and verified. Second, a mathematical model was created to evaluate the link between average queue and degree of saturation, and it was calibrated for a certain set of controlled situations, including dwell time mean and coefficient of variation.

Aniyari[3] (2018) et al. analyzed the passenger queue at the international airport of Kerala. The focus of the study was to evaluate the effectiveness of a multi-server queuing model for airport waiting lines. A mathematical queuing model was developed in this study, and comparisons were made using variance analysis (ANOVA). This study determined passengers' mean service time (μ) by considering various service times. Based on the data and using one day as a reference, it is seen that there are a lot of passengers at terminals during peak hours, implying that the utilisation factor is one.

Etaga[5] (2019) examined possible variations in bank queuing models based on geographic location. Two rural banks and two urban banks were chosen. The obtained data was analyzed using queuing models. The M/M/S queueing model generates various queuing characteristics for a waiting line. The findings revealed that queueing models vary by bank location, and banks in similar locations have similar models.

Ďutková[4](2019) used the simulation method as a tool for optimizing the costs of the Bytca post office. The goal of this study was to employ simulation methods to optimise the number of service counters to save costs. In the first phase, the queueing system is analysed to find the characterisation elements and a model appropriate for the system. A simulation program was coded according to the queueing system model and conducted several experiments.

Abdel-Aal[1] (2020) proposed an approach to apply the mathematical queueing model for the parking entry gate of the mall. For that, they collected data from shopping malls in Alexandria and Giza. To determine the distribution of arrival and service time, a goodness of fit test was also performed on the data. The **M/M/1** and **M/D/1** queueing models were used to study parking entry operations, evaluate performance metrics, and validate results against actual observations. The comparison between the collected data from the study area survey and different analytical method calculations with different models (M/M/1& M/D/1) shows that neither model is accurate. Nevertheless, the M/D/1 model seems to be closer to the surveyed data regarding the performance measures (average waiting times and average queue lengths).

AI-Kadhimi[2](2021) et al. proposed a model consisting of an open network with 10 nodes representing different real-existing serving stations of shopping malls. In this research, an analytical queueing model has been proposed to study the impact of COVID-19 on the shoppers' popularity and how the proposed system performs with mall customer arrivals. Various measures are used to examine the performance of the suggested network model. Mathematical derivations based on observed arrival and service rates conclude that the system's traffic intensity was less than 1, which assures stability.

Patel and Gor [8] (2024) carried out a study to explore consumer attitudes towards Bus Rapid Transit Systems (BRTS) in Ahmedabad, India, using factor analysis and discriminant analysis techniques. The factor analysis identified two main factors, one of which—the crowd factor—included three variables related to crowding and queueing problems. The discriminant analysis showed significant differences between the two groups based on their satisfaction levels, with the crowd factor being a key determinant, as indicated by the structure matrix. The study points out that issues like waiting lines at ticket windows, crowding at stations during peak hours and seat availability are major concerns impacting the BRTS networks in Ahmedabad. These results highlight the need to tackle crowding-related issues to improve user satisfaction and the system's overall efficiency.

3. Methodology

3.1. Establishment of BRTS Station Queueing Model

Each Ahmedabad BRTS station can be considered as a two-node queueing model. This queueing model for a BRTS station simulates how people arrive at the station, wait and then board the bus. The process of each node is as follows:

Table 3.1.1: Notations

λ_i	The arrival rate of node i (per minute)
μ_i	Service rate of node i (per minute)
ρ_i	Utilization of node i (per minute)
L_i	Average number of passengers in node i
L_{qi}	The average number of passengers waiting in line at the node i
W_i	Average time spent by passengers in the system of node i
W_{qi}	Average time spent by passengers in waiting line of node i
P_{0i}	The probability that no passenger in the system of node i

Node A: The first node of the queueing model indicates the station's Ticket window. Passengers arrive at the station following a stochastic process but with a specific average rate (λ_A), which can be considered a Poisson process. Once passengers arrive, they may need to wait in line to purchase tickets. In this node, the amount of time it takes to process a single ticket is referred to as service time, and it is an exponential Process. The mean number of passengers that can be served by one server per period is known as the service rate (μ_A). All three stations have one or two ticket windows, so the number of servers is C, and each server has an independent and identical service time. Hence, $M/M/C$, the queuing model is more appropriate for node A (Ticket window). However, those who purchase tickets online or with a smart card can avoid the first node.

Node B: Passengers wait to board the next available bus at this node. The total arrival rate for node B (λ_B) is given by the following expression,

$$\lambda_B = p_{12}\lambda_A + \lambda$$

Here, p_{12}The probability of a customer joining the second node after completing service from the first node is always 1(anyone who purchases a ticket will take a bus). So, the above equation is written as

$$\lambda_B = \lambda_A + \lambda$$

Thus, the total arrivals for node B are the direct sum of two streams: arrivals from node A (λ_A) and direct ticket holders (λ). Therefore, both nodes can be analyzed independently for studies. The inter-arrival time of the same route bus that arrives at the terminal and the time it takes for passengers to board determine the service rate (μ_B), which is exponentially distributed. Each channel (bus) in this node functions autonomously and has a distinct service time. Thus, the performance of each channel does not depend on one another. Additionally, there are infinite servers due to the self-service of all passengers at this node. Therefore, the M/M/∞ queueing model best applies to each node B channel. Table 1.1 indicates 4, 6 and 15 channels for Station X, Y, and Z, respectively.

3.1.1. Assumptions

- Both the node's arrival rate and service time follow Poisson and exponential distribution, respectively.
- The system (bus stand) has an infinite capacity to accommodate travellers.
- Events like reneging, jockeying, and baulking do not happen, and system failure is ignored.
- Each BRTS station's performance is examined in isolation, without regard to interdependencies or station-to-station interactions.
- The bus timetable is consistent, with no delays or disruptions.
- The model does not consider external factors such as traffic congestion, weather conditions, or unexpected events.

3.1.2. Queueing model

Node A: Ticket window ($M/M/C$)[6]

Using the balance equations of birth-death processes, the steady-state probabilities (p_{nA}) of the M/M/C model is given by:

$$p_{nA} = \begin{cases} \dfrac{{\lambda_A}^n}{n!\,{\mu_A}^n}\, p_{0A} & (0 \le n < c) \\ \dfrac{{\lambda_A}^n}{c^{n-c}c!\,{\mu_A}^n}\, p_{0A} & (n \ge c) \end{cases}$$

$$p_{0A} = \left(\sum_{n=0}^{c-1} \frac{{\lambda_A}^n}{n!\,{\mu_A}^n} + \sum_{n=c}^{\infty} \frac{{\lambda_A}^n}{c^{n-c}c!\,{\mu_A}^n} \right)^{-1}$$

Let $r_A = {}^{\lambda_A}/_{\mu_A}$ and $\rho_A = {}^{\lambda_A}/_{c\mu_A}$, then we have

$$p_{0A} = \left(\sum_{n=0}^{c-1} \frac{{r_A}^n}{n!} + \sum_{n=c}^{\infty} \frac{{r_A}^n}{c^{n-c}c!} \right)^{-1}$$

Consider an infinite series term and rearrange it with a suitable formula:

$$\sum_{n=c}^{\infty} \frac{{r_A}^n}{c^{n-c}c!} = \frac{{r_A}^c}{c!} \frac{1}{1 - {}^{r_A}/_c} \qquad ({}^{r_A}/_c = \rho_A < 1)$$

Therefore,

$$p_{0A} = \left(\sum_{n=0}^{c-1} \frac{r_A{}^n}{n!} + \frac{r_A{}^c}{c!} \frac{1}{1-\rho_A} \right)^{-1}$$

Now, the performance measures of the M/M/C model by means of the following formulas:

1) $L_{qA} = \sum_{n=c+1}^{\infty}(n-c)p_{nA} = \left(\frac{r_A{}^c \rho_A}{c!(1-\rho_A)^2}\right) p_{0A}$
2) $L_A = L_{qA} + \frac{\lambda_A}{\mu_A} = r_A + \left(\frac{r_A{}^c \rho_A}{c!(1-\rho_A)^2}\right) p_{0A}$
3) $W_{qA} = \frac{L_{qA}}{\lambda_A} = \left(\frac{r_A{}^c}{c!(c\mu_A)(1-\rho_A)^2}\right) p_{0A}$
4) $W_A = \frac{1}{\mu_A} + W_{qA} = \frac{1}{\mu_A} + \left(\frac{r_A{}^c}{c!(c\mu_A)(1-\rho_A)^2}\right) p_{0A}$

Node B: Waiting area for bus ($M/M/\infty$)[9]

In the general birth-death equation, consider $\lambda_n = \lambda_B$ and $\mu_n = n\mu_B$ For all n, then the Steady-state probability of $\mathrm{M/M/}\infty$ given by:

$$p_{nB} = \frac{r_B{}^n}{n!} p_{0B} \quad \text{and} \quad p_{0B} = \left(\sum_{n=0}^{\infty} \frac{r_B{}^n}{n!}\right)^{-1}$$

The infinite series in the expression for p_{0A} is equal to e^{r_B}. Therefore

$$p_{nB} = \frac{r_B{}^n e^{-r_B}}{n!} \text{ For } n \geq 0$$

The performance measures of the model are given by the following expression:

1) $L_B = r_B = \frac{\lambda_B}{\mu_B}$
2) $W_B = \frac{1}{\mu_B}$
3) $L_{qB} = W_{qB} = 0$

The above expressions are valid for each channel of node B.

- The arrival rate of individual buses can be found out by using performance measures, $L_B = \frac{\lambda_B}{\mu_B}$ which implies $\boldsymbol{\lambda_B = L_B \mu_B}$

4. Data Collection

Primary data was collected through observations at three different BRTS stations in the city: station X, station Y and station Z. For one week, peak hours at each station were selected to record the number of people entering and exiting.

Arrival Rate: The arrival rate was calculated as the number of people entering the station per minute at the ticket window. For the second node (i.e., the bus boarding point), it was challenging to determine the people's arrival rate per minute for the individual bus. Therefore, observations were made at the exit point (where passengers board the bus) to estimate the number of people in the system (L_B) during the observed period in a particular channel.

Service Rate: For the first node (ticket window), the service rate was defined as the time taken for an individual to obtain a ticket after reaching the window. This rate was consistent across all individuals. For the second node (bus boarding point), the service time was calculated as the arrival time interval between two consecutive buses of the same route number.

5. Result and Discussion

Node A: Ticket window ($M/M/C$)

Using primary data on arrival rate and service rate, performance measures of $M/M/C$ can be derived using corresponding equations.

Table 5.1. Station X

Time	λ_A	μ_A	C	ρ_A	L_A	L_{qA}	W_A	W_{qA}	P_{0A}
09:00-09:10	3.28	3.50	1	0.94	14.91	13.97	4.55	4.26	0.06
09:10-09:20	3.37	3.50	1	0.96	25.92	24.96	7.69	7.41	0.04
09:20-09:30	2.87	3.50	1	0.82	4.56	3.74	1.59	1.30	0.18

09:30-09:40	2.92	3.50	1	0.83	5.03	4.20	1.72	1.44	0.17
09:40-09:50	2.45	3.50	1	0.70	2.33	1.63	0.95	0.67	0.30
09:50-10:00	2.32	3.50	1	0.66	1.97	1.30	0.85	0.56	0.34
10:00-10:10	2.35	3.50	1	0.67	2.04	1.37	0.87	0.58	0.33
10:10-10:20	2.00	3.50	1	0.57	1.33	0.76	0.67	0.38	0.43
10:20-10:30	1.78	3.50	1	0.51	1.03	0.53	0.58	0.30	0.49
10:30-10:40	1.82	3.50	1	0.52	1.08	0.56	0.60	0.31	0.48
10:40-10:50	1.65	3.50	1	0.47	0.89	0.42	0.54	0.25	0.53
10:50-11:00	1.98	3.50	1	0.57	1.30	0.74	0.66	0.37	0.43

Table 5.1 presents the performance measures for station X. During the observation period, station X operates with a single ticket window, resulting in the system achieving its maximum utilization rate. In the initial phase, the higher utilization rate results in a larger number of individuals present within the system.

Table 5.2: Station Y

Time	λ_A	μ_A	C	ρ_A	L_A	L_{qA}	W_A	W_{qA}	P_{0A}
04:00-04:10	3.60	3.50	2	0.51	1.40	0.37	0.39	0.10	0.32
04:10-04:20	4.80	3.50	2	0.69	2.59	1.22	0.54	0.25	0.19
04:20-04:30	3.70	3.50	2	0.53	1.47	0.41	0.40	0.11	0.31
04:30-04:40	5.10	3.50	2	0.73	3.11	1.65	0.61	0.32	0.16
04:40-04:50	5.10	3.50	2	0.73	3.11	1.65	0.61	0.32	0.16
04:50-05:00	6.00	3.50	2	0.86	6.46	4.75	1.08	0.79	0.77
05:00-05:10	6.90	3.50	3	0.66	2.80	0.83	0.41	0.12	0.12
05:10-05:20	7.90	3.50	3	0.75	3.99	1.74	0.51	0.22	0.07
05:20-05:30	8.20	3.50	3	0.78	4.54	2.20	0.55	0.27	0.06
05:30-05:40	11.50	3.50	3	1.09					
05:40-05:50	11.60	3.50	3	1.10					
05:50-06:00	7.00	3.50	3	0.66	2.89	0.89	0.41	0.13	0.11

The peak hours for station Y are observed to be between 04:00 PM and 06:00 PM. From Table 5.2, it was noted that at certain intervals, the system deviated from a steady state (i.e., $\lambda > \mu$) due to the higher arrival rate of individuals. Also, the system is utilized more during this whole observation period.

Table 5.3. Station Z

Time	λ_A	μ_A	C	ρ_A	L_A	L_{qA}	W_A	W_{qA}	P_{0A}
09:00-09:10	1.83	3.50	1	0.52	1.10	0.57	0.60	0.31	0.48
09:10-09:20	1.87	3.50	1	0.53	0.61	0.53	0.33	1.15	0.61
09:20-09:30	1.63	3.50	1	0.47	0.87	0.41	0.54	0.25	0.53
09:30-09:40	2.10	3.50	1	0.60	1.50	0.90	0.71	0.43	0.40
09:40-09:50	2.01	3.50	1	0.57	1.35	0.78	0.67	0.39	0.43
09:50-10:00	1.41	3.50	1	0.40	0.68	0.27	0.48	0.19	0.60
10:00-10:10	1.34	3.50	1	0.38	0.62	0.24	0.46	0.18	0.62
10:10-10:20	1.27	3.50	1	0.36	0.57	0.21	0.45	0.16	0.64
10:20-10:30	1.41	3.50	1	0.40	0.68	0.27	0.48	0.19	0.60
10:30-10:40	1.67	3.50	1	0.48	0.91	0.44	0.55	0.26	0.52
10:40-10:50	1.31	3.50	1	0.37	0.60	0.22	0.46	0.17	0.63
10:50-11:00	1.20	3.50	1	0.34	0.52	0.18	0.44	0.15	0.66

During peak hours, station Z works with 1 ticket window. From Table 5.3, it was observed that there was no overcrowding or overutilization of the system at the ticket window throughout the observation period.

Node B: Waiting area for the bus ($M/M/\infty$)

By using the arrival rate equation of $M/M/\infty$ model (i.e. $\lambda_B = L_B\mu_B$) The following graphs indicate each channel arrival rate for respective stations.

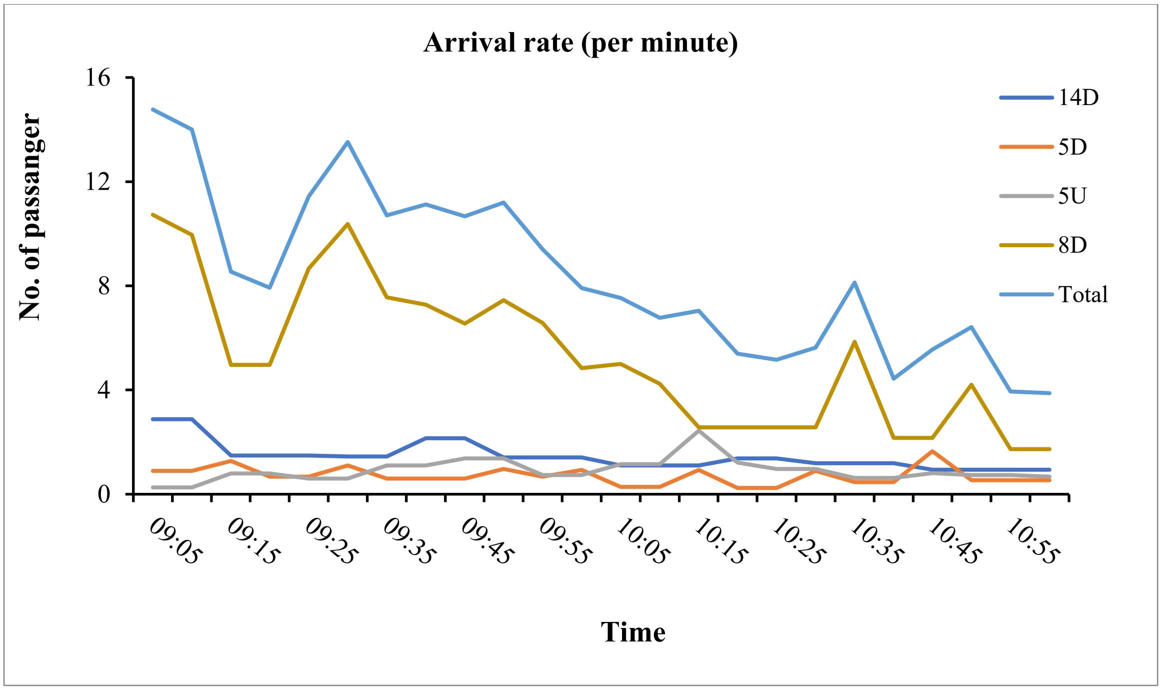

Figure 5.1 Station X

Figure 5.1 demonstrates that the station experienced its highest passenger flow during the initial observation period. This surge is primarily driven by passengers boarding bus route 8D, which accounts for the majority of traffic density at the station during peak hours. In contrast, passengers from other bus routes contribute minimally to the overall bottleneck, as their arrival rates remain significantly lower.

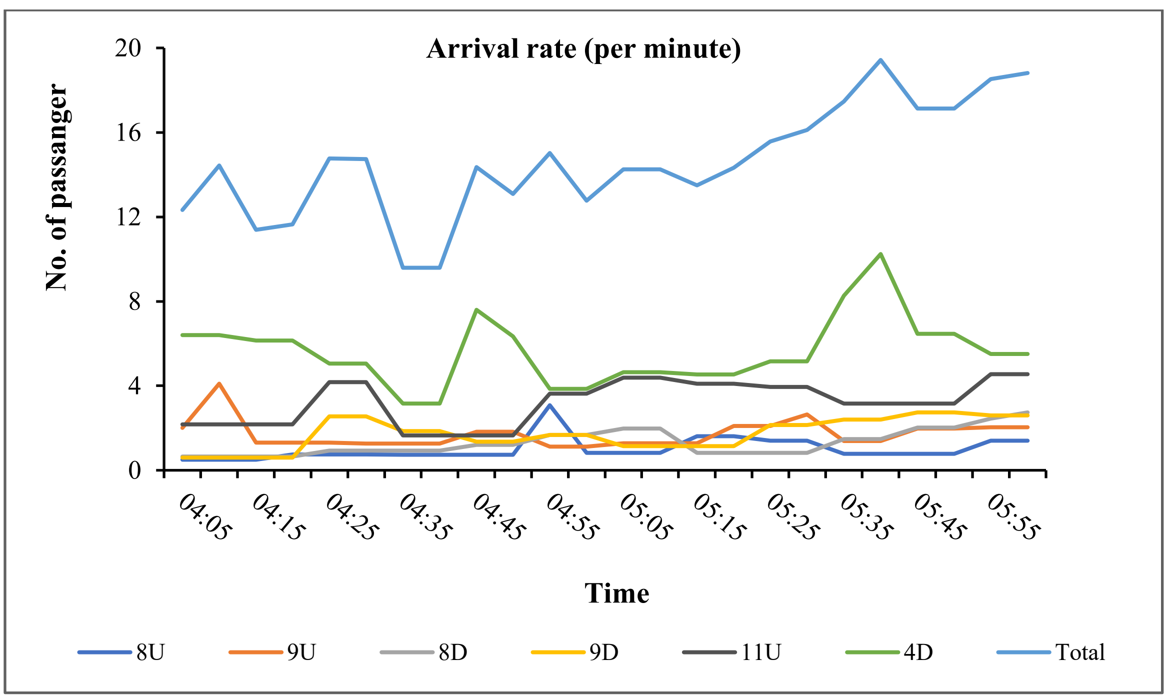

Figure 5.2 Station Y

As Figure 5.2 shows, the total arrival rate of station Y is not highly dependent on any one specific channel. However, channel 4D displays consistently higher arrival rates compared to other channels throughout the observation period. It is also found that the arrival rate increases over a period of time for each channel.

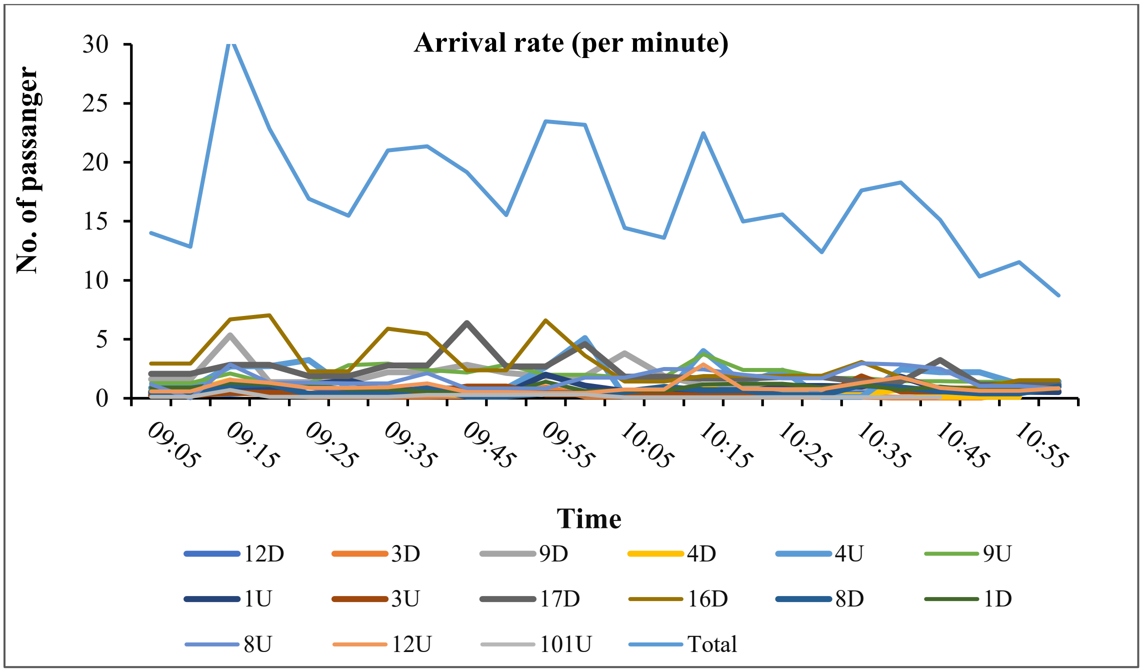

Figure 5.3 Station Z

Figure 5.3 demonstrates that station Z experiences its highest passenger concentration at Node B. Unlike other stations where specific bus routes dominate traffic patterns, the crowding at Node B emerges from the cumulative effect of all channels' arrival rates rather than any single high-demand route.

6. Proposed system

6.1. Node A: Ticket window (M/M/C)

6.1.1. Station X

Table 5.1 demonstrates that the current BRTS ticket window operates under over-utilized conditions, leading to passenger congestion and service delays. We evaluate the potential impact of adding the server to the system to address this.

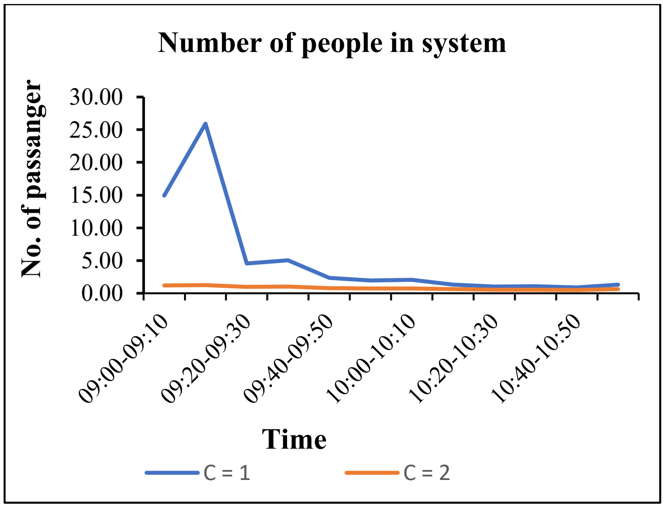

Fig. 6.1 Station X

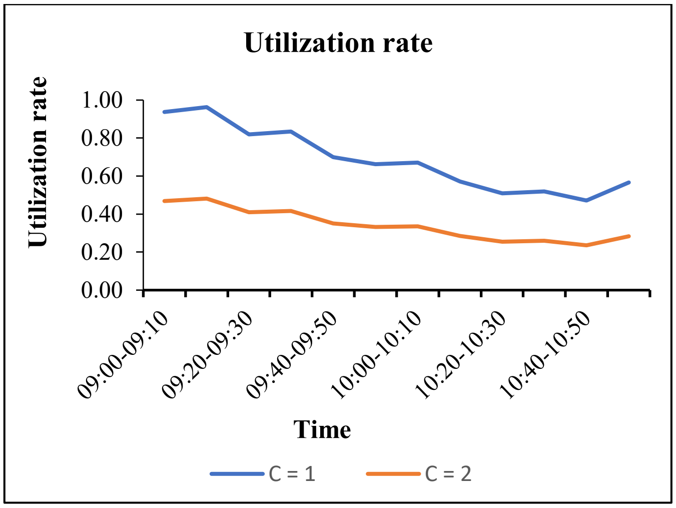

Fig. 6.2. Station X

Figures 6.1 and 6.2 demonstrate that adding a second server significantly reduces congestion and improves service efficiency during peak demand (before 9:50 AM). The system stabilizes afterwards, with one server adequately handling passenger flow. The following suggestions are proposed:

Targeted Server Placement

- A second server is only necessary during the initial peak period (e.g., 9:00 AM–9:50 AM).
- Beyond this window, a single-server configuration maintains optimal performance (ρ < 0.7).

Cost-Efficiency Consideration

- Unnecessary operation of a second server post-9:50 AM would incur avoidable staffing and maintenance costs.
- Dynamic resource allocation (e.g., flexible shift scheduling) could optimize operational expenses while maintaining service quality.

6.1.2. Station Y

Similar to station X, this station requires an additional channel, increasing the total channel from 2 to 3 and 3 to 4 during operations.

The analysis reveals that while the system maintains moderate passenger density levels, it operates at consistently high utilization rates, potentially compromising service quality during peak periods. Furthermore, it is indicated that the system is not steady at the end of the observation period.

Hence, unlike station X—where the extra channel was only needed temporarily—Figures 6.4 indicate that the additional channel remains necessary throughout the observation period.

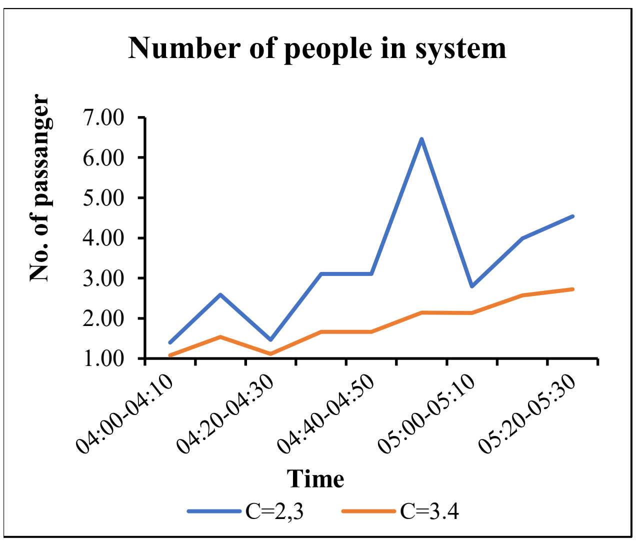

Fig. 6.3. Station Y

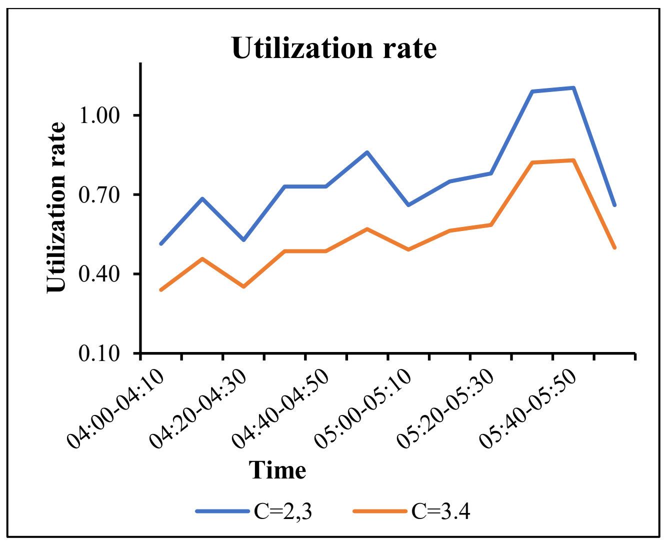

Fig. 6.4. Station Y

Despite this expanded capacity, the system still experiences periods of over-utilization (ρ > 0.7), particularly from 05:30 to 5:50 PM. This suggests that while the additional channel alleviates congestion, demand occasionally exceeds the enhanced capacity. So, it is proposed to maintain four active channels but monitor for potential further adjustments if overcrowding remains.

6.1.3. Station Z

Table 5.3 determines that station Z's ticket window operates at optimal capacity, with a balanced demand-supply ratio ($\lambda < \mu$). Utilization factor (ρ) maintains stable levels (ρ < 0.7) throughout observation periods.

Hence, station Z's existing infrastructure meets demand requirements without requiring expansion. Maintenance of current resource levels is recommended unless future traffic patterns show significant demand growth.

6.2. Node B: Waiting area for the bus (M/M/∞)

6.2.1. Station X

Numerical analysis of Node B (Figure 5.1) reveals that overcrowding at station X primarily stems from the high arrival rate of passengers for Route 8D, which currently operates at a service time of 6.32 minutes. We propose increasing the bus frequency by reducing the service time to 4 minutes to address this congestion. Figure 6.5 demonstrates the potential crowd reduction achievable through this adjustment.

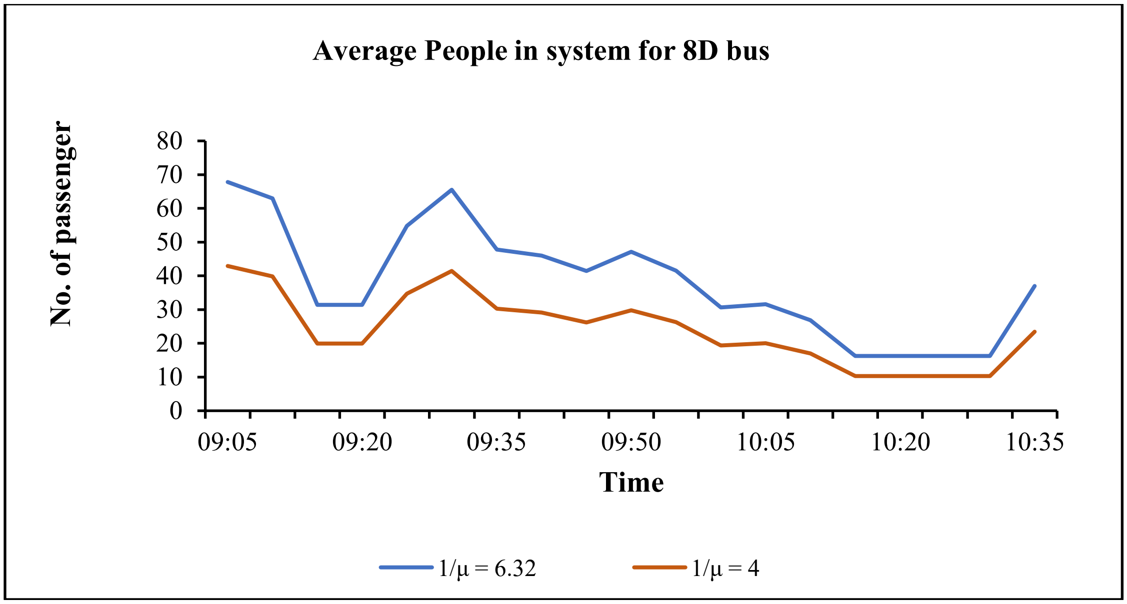

Fig. 6.5 Station X

Key Findings
1. The modified 4-minute service interval significantly decreases passenger accumulation at Node B.
2. During peak hours (<10:00 AM), this increased frequency effectively manages the crowd.
3. Post-10:00 AM, the original 6.32-minute service time can be maintained to balance operational costs.

While higher frequency may increase system costs during peak hours, it improves overall passenger satisfaction, so the benefits extend beyond station X, as reduced crowding allows for smoother boarding at subsequent stations.

6.2.2. Station Y

Similar to station X, this station also requires adjustments to the frequency of Route 4D bus. Currently, this route operates at 10-minute intervals. Reducing the service time to 7 minutes, as shown in Figure 6.6, demonstrates a significant reduction in station crowding of bus number 4D.

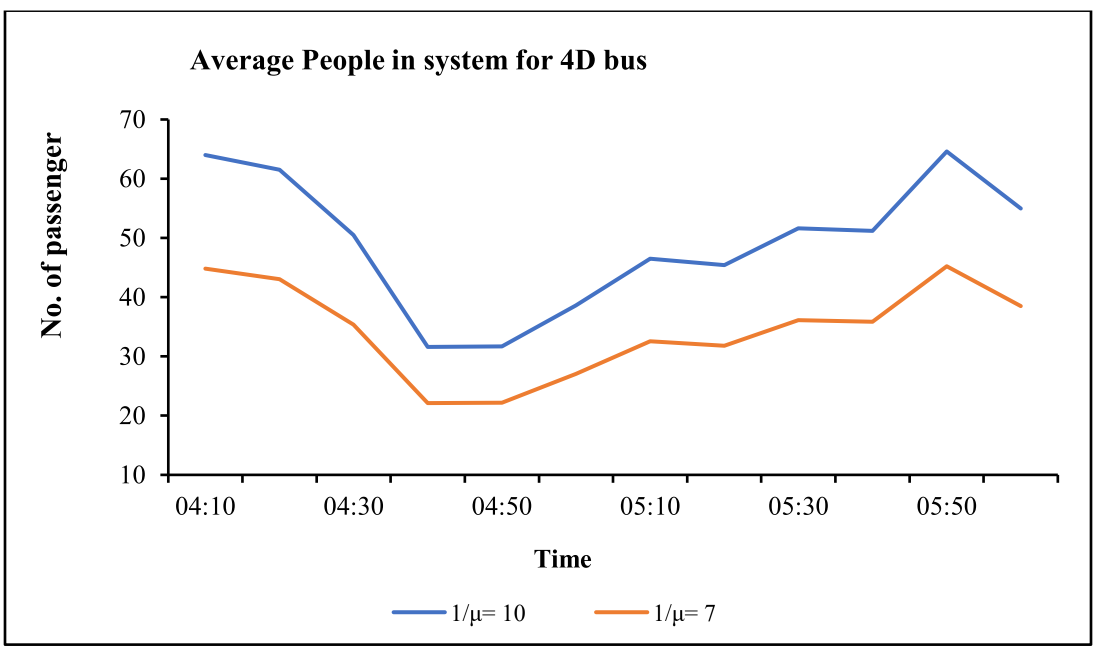

Fig. 6.6 Station Y

6.2.3. Station Z

Figure 5.3 demonstrates that station Z is overcrowded because almost 15 buses visit that station. Station Z is the starting point for two buses, and the stations come in their route for other buses. It is also found that (table 5.3) the arrival rate for node A is also lower, so there is no higher arrival from node A to node B.

Hence, overcrowding is accrued due to mainly two reasons,
1. Interchange of the bus by customer at this station.
2. The station is a part of the routes of many buses.

To resolve this issue, the following few alternatives can be possible if they fit into the regulation of BRTS:
1. Shift the starting point of the two originating buses (Bus 17D, 16D) to a nearby station to divert passenger traffic.
2. Rerouting some buses to skip this station and stop at the nearest station instead.

These minor changes in routes can help a lot and improve the overall efficiency of station node B. Moreover, these changes do not lead to an increase in operational costs.

7. Conclusion

This study evaluated congestion management strategies across multiple BRTS stations, identifying route-specific optimizations and ticket window adjustments to improve passenger flow and system efficiency. Key findings include:

7.1. Station-Specific Solutions

- Station Z requires redistributing bus routes rather than frequency changes, as overcrowding stems from its role as an interchange hub.
- Ticket window optimization at two out of three stations showed that dynamic staffing (e.g., adding windows during peaks) reduced queue length.

7.2. Route-Based Frequency Adjustments

- Reducing Route 8D's service interval from 6.32 to 4 minutes at station X decreased the peak crowd.
- A similar adjustment for Route 4D (10 to 7 minutes) at station Y reduced the average wait time.

Recommendations

- Adopt targeted frequency reductions for high-demand routes (e.g., 8D, 4D).
- Optimize route paths for interchange-heavy stations (e.g., skip-stop patterns at Station Z).
- Implement flexible ticket window management based on real-time demand.
- Monitor post-implementation metrics (crowding indices, wait times) to refine strategies.

Future Scope

- Scalability Research: Examine application potential for other BRTS networks with similar congestion challenges.
- Inter-station Coordination: Study interdependence between stations to optimize system-wide performance.
- Multi-modal Application: Extend the methodology to metro and railway stations for broader transit solutions.
- Route-specific Analysis: Conduct focused studies on individual bus routes to identify targeted improvements.
- Cost Evaluation: Perform detailed cost-benefit analysis of proposed operational changes.

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