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Research Article

Assessment on the Current and Future Performance of Addis Ababa Light Rail Transit Service Using Mathematical Modeling

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Congestion and extended passenger waiting time are some of the key issues that the Addis Ababa Light Railway Transit service (AALRT) faces. Passengers waited an average of 14.33 minutes, resulting in congestion of passengers. This is why the study set the main objective to develop an optimization model for improving AALRT service. The study began by developing the characteristics of the data to evaluate the congestion problem as part of its approach to achieving this objective. Second, on the selected station, an optimization model was constructed. Then an alternate model has been created by evaluating the previous model's performance. Finally, without expanding the system, the researcher evaluates its effective service life. Using a combination of queuing theory and Monte Carlo simulation approach, the study used case study research methodology by taking the most congested metro station in both corridors and directions of AALRT at peak hours. Primary data were collected from each station and the relevant authority, while secondary data were conducted from the literature. The finding indicates that the congestion rate of AALRT reaches up to 25.3% and the percentage of the extra capacity of the tramcar required up to 115%. Therefore, it was found that currently adding two single tramcars could reduce the waiting time up to 9.52 minutes and the congestion up to 99%. The new model indicates the company can improve the service by increasing the number of tramcars per hour and replacing single tramcars with double tramcars up to the year 2047 without expansion of the infrastructure.

1. Introduction

Addis is the capital and largest city of Ethiopia. According to the 2007 census, the city has a population of 2,739,551 inhabitants, and United Nations population projections show the current metro area population of Addis Ababa in 2021 is 5,228,000, which in turn has led to the demand for transportation is rapidly growing. The increasing demand for Addis Ababa transportation has created long queues in every aspect of traffic. Congestion is becoming more and more common occurrence around the city. Rail travel, often known as train transport, is one of the most essential, widely used, cost-effective ways of commuting, cargo carrying across long, and short distances to alleviate the transportation problem. The Ethiopian government commissioning to address the congested roads of the capital, Addis Ababa with a new urban metro, largely funded by the Export-Import Bank of China and constructed by China Railway Group Limited at USD 475 million [1].

Addis Ababa, which houses close to 25% of the city dwellers, is the capital city of Ethiopia, the largest metropolis in the country, and among Africa's fastest-rising cities. The Addis Ababa light rail transit (AALRT) is Eastern and sub Saharan Africa's first light rail and rapid transit system placed into operation in 2015. It is an electrified light rail transit system with 39 stations and 34.25 kilometers of train lines. AALRT has two lines. Trains on both LRT lines are limited to 80 km/h, thus their typical operating speed is 65 km/h, designed to reduce and control traffic congestion in Addis Ababa [1].

However, rising demand for Addis Ababa transit has resulted in lengthy lines similar to traffic congestion. This backlog or congestion causes a variety of issues. Traffic congestion has been an ever-growing chronic problem in the transportation system since the creation and mass manufacture of vehicles, according to Taddesse W. [2]. Due to economic and demographic expansion, all major cities in developed and developing nations are seeing an increase in travel demand [3]. Traffic congestion directly impacts commuters by increasing travel time, increasing wait length, increasing fuel costs, delaying important appointments and jobs, and reducing productive hours; it also has an indirect impact on the living standard and the environment [4]. As a result, traffic congestion costs both road users and cities a large amount of money.

According to statistics collected over the last six years, this AALRT serves an average of 90,989 passengers per day, with an average waiting time of 17 minutes. The management of the AALRT has long- and short-term aims to reduce the average wait time to 10–12 minutes [5]. According to Stoilova and Stoev [6], railway network businesses frequently need to model and simulate to reduce passenger wait times. This requirement generally arises as a result of infrastructure development or maintenance, or the addition of additional tramcars to an existing rail system.

Mala [7] demonstrated how queuing theory can be used to select the best service by balancing wait time and cost. A limited study has been done to clarify the AALRT service condition as well as the mismatch between service and demand. This gap motivated the researcher to conduct in-depth investigations utilizing integrated queue theory and Monte Carlo simulation methods to assess the optimization of service and cost in the AALRT project.

2. Research Methods and Procedures

2.1. Description of the Case Study. AALRT has two lines. The first heavily-used route is the North-South corridor, a 17.35-kilometer line that starts from the city center Minilik II square passing through in the north, and heads a little distance to the west to access Merkato and Autobus Tera (the intercity bus terminal), Lideta, Legehar, Meskel Square, Gotera and to industrial areas in the south of the city Kality serving 22 stations.

And the second heavily-used route is the East-West corridor, 16.9 kilometers line running from Torhailoch and passing through Mexico Square, Legehar, Meskel Square, and Megenagna to Ayat serving 22 stations with the two lines sharing a 2.7 km section of the track in the city center. This highway connects Ayat, CMC, Gurdshola, and the area west of Torhailoch, which are all major residential and real estate development locations. Meskel Square is Addis Ababa's main public meeting spot, while Meganagna Square serves as a significant transit hub and commercial hub. Megenagna is where the East-West corridor meets the ring road.

2.2. Research Methods. The work involves several methods and steps to carry out the task thoroughly and meet the objective of the research. First, a literature review from different books, articles, published journals, codes, and standards; preceding and paper on the topic was done. This serves as a good stage to start and schedule the study properly. The main objective of this research is to identify and develop an optimization model for all stations throughout the stretch of both East-West and North-South rail corridors of AALRT. Thus, it is required to assess to what extent the congestion of passengers exists. Besides, applying practices and tools of the congestion problem-solving model and computer-aided simulation software solve the problem. Providing optimum service is one of the most critical actions in the railway service under operation. For this purpose, it is necessary to develop a model to ensure effective management of the metro station. This is used to guide the planners and estimators to maximize transit service; and forecast activity durations. Finally, it is used to lower congestion and optimize the waiting time.

2.2.1. Data Sampling and Collection. Quantitative data were gathered for this study. Quantitative methods are those that deal with measurable data [8], used to investigate the congestion problem by using numbers.

The congestion of passengers at the station could be a small number of tramcars, late arrival of tramcar or the number of passengers is beyond the capacity of the tramcar. So peak hour data have been collected for three months at all stations of both corridors of AALRT such as passenger's arrival time, tramcars arrival time, the number of passengers arrived, the number of tramcars arrived, and so on quantitatively as first-hand data. To meet the objective of this research, the secondary data have been obtained from a desk study of various works of literature and concerned authorities. In the same way, some quantitative data were obtained from the desk study of various documents of AALRT.

2.2.2. Data Analysis and Modeling Methodology. A queuing problem can happen due to imperfect matches between the customers and service facilities like AALRT which necessitate the use of queue theory to minimize the waiting time of the passenger. The previous study demonstrated how the queuing theory was applied to optimize a small businesses [9], healthcare [10], supermarket checkout [11], subway stations [12], ticket windows [13], multi-stage production lines [14], and utilization of concreting equipment in construction [15]. The optimization of call center staffing [16], transportation of sugar cane to mills [17], and ranked checklist of risks [18] all used the Monte Carlo simulation method. One of the many pieces of literature examined in this field is the application of queuing theory to automated teller machine (ATM) facilities using Monte Carlo Simulation [19]. To achieve the best representation and eliminate the shortcomings of the aforementioned studies, the analysis of the AALRT system was carried out utilizing a combination of queuing theory and the Monte Carlo simulation optimization method.

In part of the research, the researcher solves the first and second specific objectives as follows: the first objective has been solved by determining the probability distribution of the data collected to identify the extent of congestion. This justification was undertaken by using distribution fitting software like @RISK. The second objective has been addressed by collecting and comparing data at all stations of both corridors of passenger flows. The third specific objective has been addressed by forecasting the future performance of the system by considering the current performance with the population growth rate.

Besides, the Monte Carlo simulation model was employed to address all specific objectives by developing a new model based on the data collected and the probability distribution. In this case, the researcher would choose the theory for developing the optimization model based on the characteristics of data by random sampling rather than a first-come-first-served discipline.

2.3. Procedures. The objective of this research paper is achieved through the following step and processes.

(1) Problem identification
  (i) the foundation for everything to follow in research
  (ii) used to find out the significance of the research
  (iii) to identify the congestion problem that happens during rush hour

(2) Stating general and specific objectives
  (i) the aim which the enquirer seeks to bring about as the result of completing the research
  (ii) that used to develop a framework for the study
  (iii) showing what exactly to be studied, and states the desired outcome from the research

(3) Literature review
  (i) to give an overview of what has been said regarding the study under consideration
  (ii) to identify the knowledge area of the subject matter through critical review
  (iii) to identify processes and practices to be included in the planning and modeling process of the current study
  (iv) to know the way and the content of the current study by going through the subject area
  (v) to study and identify the state-of-the-art, importance, and way of simulation implementation in the service industry with more emphasis on light railway optimization

(4) Data collection was conducted through
  (i) direct counting as primary data, and
  (ii) reading documents as secondary data to develop the optimum model of the passenger congestion

(5) Through the use of state-of-the-art @Risk computer-aided simulation software, a case study was conducted to analyze the current transportation process and develop the best solution.

(6) Data analysis and discussion;
  (i) to analyze the collected data using simulation software and spreadsheets to attain the objective
  (ii) to determine the relative importance of the optimization model simulation in the LRT passenger congestion, waiting time, and cost of the company
  (iii) to develop a useful supporting tool in the transportation service of AALRT at specified congested stations

(7) Finally, conclusions have been drawn and recommendations have been forwarded to the company, the government, and researchers using the developed model, analysis, and discussion.

2.4. Research Design. In Figure 1 depicts the basic outline of the research design. The literature review follows the abovementioned research problem and objectives. Following that, the identification of data required to deal with and address the situation was taken into consideration. Primary data were gathered from the field, while secondary data were gathered from various documents kept at the subject company's office and from various works of literature. The data were used to construct the model, which was then followed by simulation and analysis. Finally, based on the findings of the analysis, conclusions were drawn and recommendations were made for the development of improvement strategies.

3. Analysis, Result and Discussion

3.1. Selection of Congested Corridor, Shift and Station. Addis Ababa Light railway transit is constructed on East-West (E-W) and North-South (N-S) corridors. AALRT serves for 16 hours in two shifts called the morning and the afternoon. The morning shift is from 6 : 00 AM up to 2 : 00 PM, and the afternoon shift is from 2 : 00 PM up to 10 : 00 PM. Its peak hours are from 7–9 AM and 10–12 PM in the morning and afternoon, respectively.

As per the interview of AALRT operation control center (OCC) worker, data obtained from the past six years of operation, and results from this study, the East-West corridor is congested as compared to the North-South corridor. Similarly, the East-West direction is congested in the morning shift as compared to the afternoon shift and the afternoon shift is congested as compared to the morning shift in the West-East (W-E) direction. And the North-South corridor is the next congested route. In the North-South direction, the afternoon shift is congested compared to the morning shift, and in the South-North (S-N) direction, the morning shift is congested compared to the afternoon shift.

After the selection of congested shifts in both corridors, selections of congested stations have been done. Accordingly, in the East-West corridor and direction, from Management Institute to Legehar stations have been identified as congested stations. As a result, Megenagna and Haya Hulet 1 are the most congested in this corridor and direction. Stations from Stadium to Civil service have been recognized as congested in the West-East direction. As a result, Megenagna and Haya Hulet 1 are the most congested stations in this direction. Similarly, traffic congestion has been found

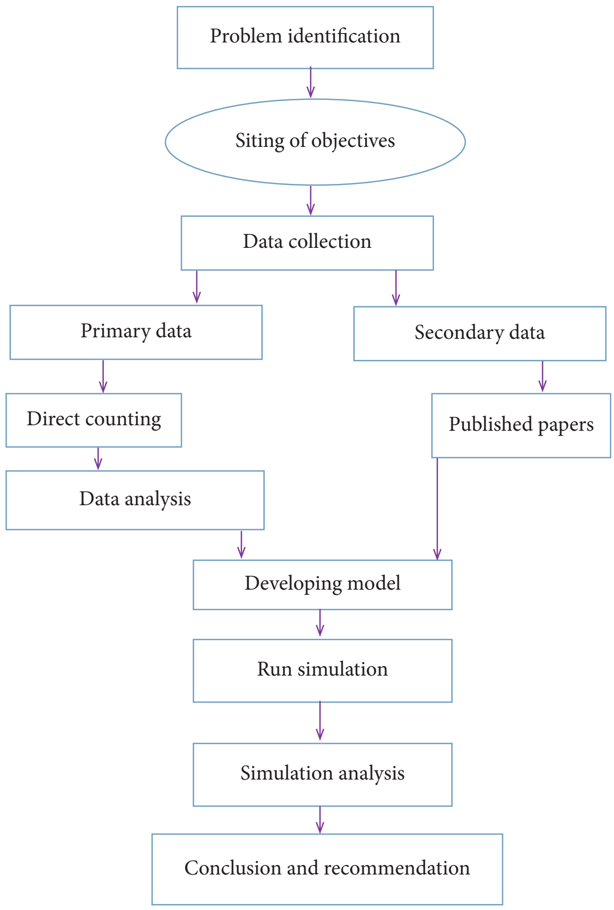

Figure 1: Data collection, model creation, and research completion steps in the research process.

throughout the North-South corridor and direction, from Tegbareid to Adey Ababa. As a result, Stadium and Legehar are the most congested on this route. Stations between Nifas Silk 2 and Tegbareid have been recognized as congested stations. As a result, the most congested stations in this direction are Stadium and Legehar.

3.2. Data Collection and Validation. Different models, such as queue theory, Markova chain, Monte Carlo simulation, and others, are used to solve the congestion problem. However, to keep to one theory, the researcher used @RISK software to find the probability distribution.

3.2.1. Statistical and Probability Distribution of Data. The @RISK software includes functions for generating random numbers from a variety of probability distributions. Many of these software modules provide pull-down selections for these distributions, and they are likely to be used. One or more parameter values are connected with each distribution in the @RISK program [20]. To properly describe the distribution, these parameter values must be specified. The distribution determines the number, meaning, and order of the parameter values [21]. Table 1 summarizes the distributions (in alphabetical order) and parameter values.

Table 1: Probability distributions and their parameter values.

Distribution function	Abbreviation	Parameter values
Binomial	Bin	s, p
Negative binomial	Negbin	n, p
Exponential	Expo	Mean
Poisson	Pois	Mean
Uniform	Unif	Min, Max

3.2.2. Data Collection and Summary of Data. Using @RISK, the statistical and discrete probability distribution of morning and afternoon peak hours of passengers departed, tramcar arrival, and tramcar capacity, at Haya Hulet 1, Megenagna, Legehar, and Stadium stations in specified corridors and directions have been identified. Tramcar capacity is the multiple of tramcars arrival with its design capacity; of 286 passengers. However, the passenger departure in the starting station is the boarding passenger and it is replaced by the difference of boarding and alighting of passengers arrivals in intermediates stations and passenger departure from the previous station.

The result of the goodness of fitting is uniform, the binomial, negative binomial, and Poisson distribution. Uniform distribution happened when the data are uniformly distributed within a specific interval. Given a success probability p for each trial, the binomial distribution represents the likelihood of x successes in n trials in the discrete distribution. The negative binomial distribution is a discrete probability distribution of the number of successes in a sequence of independent and identically distributed events that occur before a given (non-random) number, r failures. Sample graphical probability distribution Haya Hulet 1 station at the peak hour of AALRT are shown in Figures 2 and 3 shown below.

3.3. Modeling of AALRT by Monte Carlo Simulation. Software for micro and macro simulations like VISSIM and VISUM is available. It is the standard for multimodal traffic flow planning, simulations, and modeling of transportation networks and demand, as well as for planning public transportation that analyzes multimodal traffic flow.

The congestion problem of AALRT can be solved through different models like queue theory, Markova chain, Monte Carlo simulation, and the like. However, to stick to one theory, the researcher found the probability distribution of passengers by @RISK software.

3.3.1. Assumption and Summary of How the Model Developed

(i) The assumption made in the development of the Monte Carlo simulation

   (i) None peak hours or out of 7–9 AM and 4–6 PM is the normal operation by assuming the rate in and out are equal in each station.
   (ii) 9–10 AM and 6–7 PM arrivals and the previous peak hours transferred to these hours are manageable through the existing system.

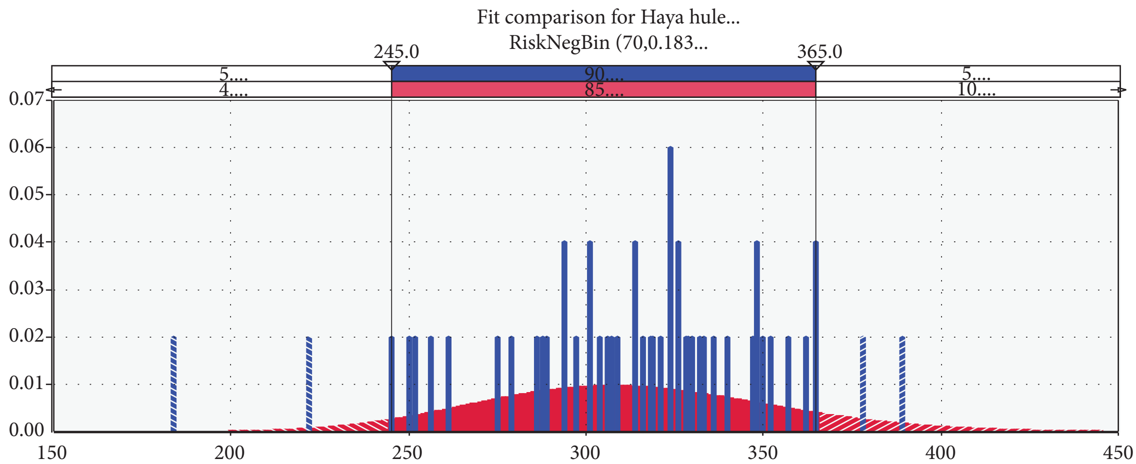

Figure 2: The probability distribution of passengers departed per tramcar for peak hours at Haya Hulet 1 station in the W-E corridor.

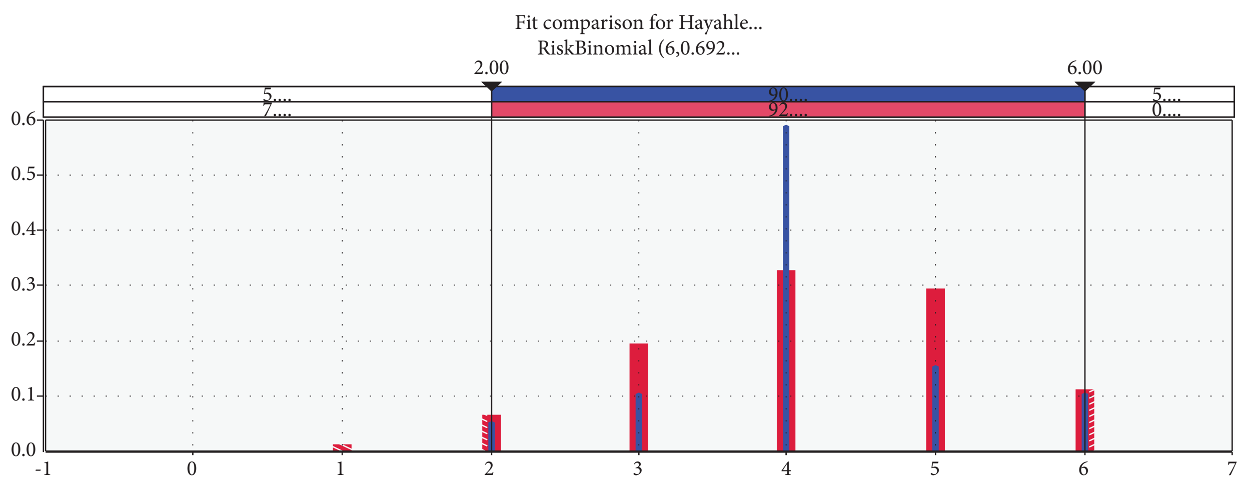

Figure 3: The probability distribution of hourly tramcar arrival for peak hours at Haya Hulet 1 station in the E-W corridor.

(iii) 3–4 PM and 6–7 AM are manageable through the existing operation, and there are no passengers transferred to the next station.

(iv) During peak hours, the tramcar collects a large number of passengers from the intermediates station, and it became fully utilized.

(ii) The model was developed as follows:

(i) Data collected from most congested stations

(ii) The goodness of fit was checked through MS-Excel addin @RISK software to get the probability distribution.

(iii) Since probability distribution was unfit for queue theory and Markov chain, Monte Carlo simulation was selected to generate random numbers.

(iv) One thousand random numbers were generated from each probability distribution for passenger departure and tramcar arrival at selected stations.

(v) The average capacity of the passenger was calculated from randomly generated average tramcar arrivals.

(vi) The extra passenger can be transferred to the next hour with the first come first served principle. But the Monte Carlo random number generation with extra passengers was addressed by adding extra tramcars.

(vii) Calculation of tramcar capacity for an additional passenger was conducted based on the extra passengers of each peak hour.

(viii) Summary of optimization and comparison of the actual and ideal solution conducted.

For passenger departure and tramcar arrival, a Monte Carlo random number was created. Only the extra passengers created at selected stations during their corresponding peak hours for the first 1000 random numbers generated with their average value generated are listed in this section for one governing station from the East to West corridor and one governing station from the North to South corridor. The numbers of extra passengers are provided as an appendix for the other stations to investigate the congestion of AALRT.

3.3.2. Investigation of Congestion of AALRT at Some Selected Stations. Congestion is defined as that is too overcrowded or blocked, posing a hazard [22]. Furthermore, congested roads and cities have excessive traffic, making transportation difficult. When "users share a service system with limited capacity," this occurs. The congestion rate is computed by averaging the amount of crowdedness throughout a train line's busiest hour, according to Moussa et al. (2014). Congestion is determined using traffic intensity, and it can occur when $\rho > 1$, the LRT is overcrowded, and a queue forms; however, when $\rho < 1$, the LRT is not overloaded, and no queue forms [24] The calculation is done through;

$$\begin{aligned} &\textit{Percentage of overcrowded}\\ &= \frac{\textit{additional passenger}}{\textit{capacity of tramcar}} x100,\\ &\textit{Percentage of extra tramcar required}\\ &= \frac{\textit{total no of additional passenger occured}}{\textit{total number of random number generated}} x\frac{100}{286}. \end{aligned} \tag{1}$$

The percentage of extra tramcar required is the indication of the amount of time overcrowded occurs in a particular interval. Therefore, from Monte Carlo simulation random number generation, the congestion rate or crowdedness during a train line's busiest hour in each station is calculated and summarized as follows:

In the E-W direction, 96% of additional tramcar is required at Megenagna and 115% at Haya Hulet 1 metro stations, according to Table 2. In the W-E direction, 95.6% of additional tramcar is required at Haya Hulet 1 and 96.9% at Megenagna metro stations. In the N-S route, 102% more tramcar is needed at Stadium and 106.3% at Legehar metro stations; in the S-N direction, 95.5% more tramcar is needed at Stadium and 97% at Legehar metro stations.

Furthermore, the congestion/overcrowded rate of the AALRT in the E-W direction is 22.5 and 22.6% at Haya Hulet 1 and Megenagna metro stations, and in the W-E direction is 22.5 and 22.9% at Haya Hulet 1 and Megenagna metro stations, in the S-N direction is 22.5 and 22.9% at Legehar and Stadium metro stations, and in the N-S direction is 22.7 and 23% at Legehar and Stadium metro stations. As a result, the Addis Ababa LRT is congested.

3.4. Optimization of AALRT Service on Selected Stations. If there has been congestion and the data have been categorized using a given probability distribution, the next step should be to find a solution to the problem. The answer to the current situation would be to create a new model based on the real data. The goal of this queueing model would be to maximize service while lowering costs. In this study, optimizing the service entails reducing customer wait times or queuing lines on the AALRT platform by increasing the number of tramcar arrivals while keeping service costs in account.

Using a statistical summary of passenger departures, tramcar arrivals, and tramcar capacity, 1,000 random numbers were created using the probability distribution to determine additional tramcar capacity. As noted below, this additional passenger would be used to find more tramcar capacity to alleviate passenger congestion.

Histogram representation of the extra passenger due to congestion shows the summary of the additional capacity of tramcar required. This histogram shown in Figures 4 and 5 reveals the appropriate expression of the extra tramcar with its equivalent capacity.

Table 3 indicates that the current waiting time of the Addis Ababa Light railway is 14.33 minutes as per the current data simulated through Monte Carlo methods. The 14.33 minutes is the average of 14.37, 13.95, 14.29, and 14.72 minutes of the morning and afternoon waiting time, respectively, in the specified stations.

The optimization of AALRT through the Monte Carlo simulation method has shown the above study concludes that adding two single extra tramcars can reduce the waiting time up to 32.43% and the congestion up to 88% in the morning at Haya Hulet 1 station, 31.76% and the congestion up to 99% in the afternoon at Megenagna station, 32.26% and the congestion up to 99% in the morning at Legehar station, 32.88% and the congestion up to 99% in the afternoon at Legehar station.

The maximum waiting time that can be minimized based on the designed passengers' tramcar capacity and geometry AALRT is 7 minutes [25]. The output of this optimization study, 9.71 minutes in the E-W direction, 9.52 minutes in the W-E direction, 9.68 minutes in the S-N direction, and 9.88 minutes in the N-S direction is acceptable based on the current capacity of AALRT since the waiting time greater than the minimum waiting time of the basic study. Therefore, in the case study of Addis Ababa Light railway stations in both corridors and directions, the best service would be when the organization adds 2 single tramcars. This will reduce waiting time up to 32.88% and congestion up to 99% as stated in Table 3.

3.4.1. Summary of Optimization Solutions. The researcher examines several situations after obtaining information about LRT optimization at some of those selected stations through simulation. According to an interview with AALRT OCC staff, the basis for this work is that an existing LRT service comprises two corridors and two directions with two shifts: one from 6 : 00 AM to 2 : 00 PM, and the other from 2 : 00 PM to 10 : 00 PM. Our simulations show that this optimization approach is best with a steady-state condition during morning rush hours of 7–9 a.m. and afternoon rush hours of 4–6 p.m. See Figure 6 for an example of the results obtained by running a Monte Carlo simulation with the assumption that each service provider works two shifts. The

Table 2: The percentage of overcrowded and extra trains required at selected stations.

Corridor	Direction	Peak hours	Station	Percentage of the extra capacity of one tramcar required	Percentage of overcrowded
E-W	E-W	7–9 AM	Haya Hulet 1	115	22.5
			Megenagna	96	22.6
	W-E	4–6 PM	Haya Hulet 1	95.6	22.5
			Megenagna	96.9	22.9
N-S	S-N	7–9 AM	Stadium	102	24
			Legehar	106.3	25.3
	N-S	4–6 PM	Stadium	97	23
			Legehar	95.5	22.7

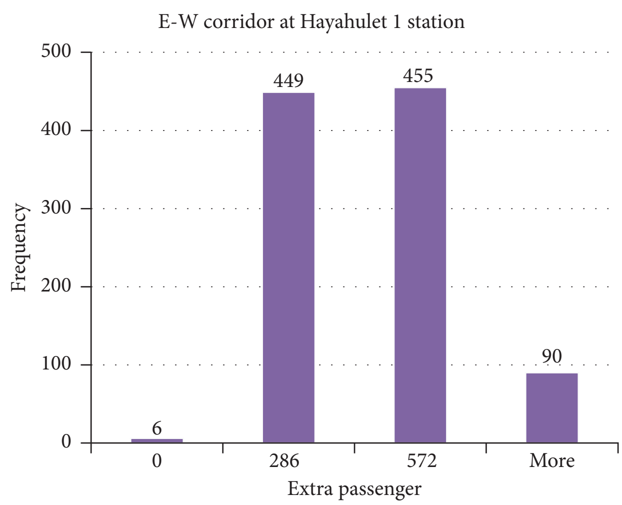

Figure 4: Histogram representation of extra passengers at Haya Hulet 1 station.

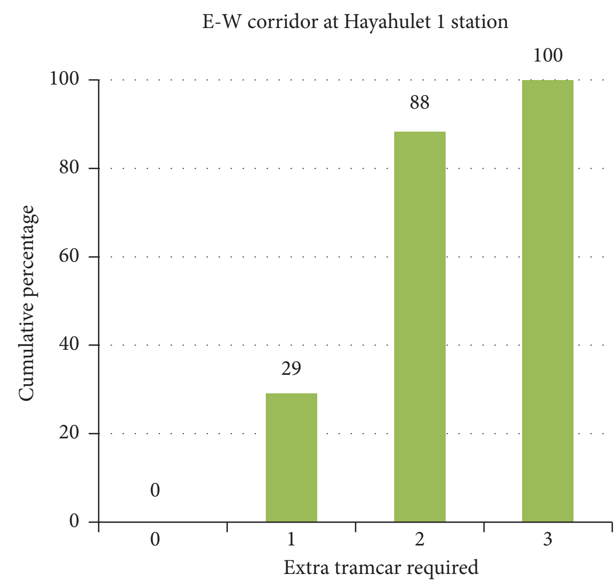

Figure 5: Histogram representation of the corresponding extra tram car required at Haya Hulet 1 station.

blue zigzag curve indicates the ideal tramcars provided by the Monte Carlo simulation, whereas the three straight lines represent the number of tramcars obtained from the simulations by the researcher. The red straight line shows when two independent tramcars were added to improve service, the green straight line shows when a single tramcar was added to maintain the current system's average service, and the yellow straight line shows the average number of tramcars existing.

The ideal, actual, and extra numbers of tramcars at Haya Hulet 1 station from 4–6 p.m. of the afternoon shift are depicted in Figure 6. The actual straight line provides a clear indication of the model's steady-state performance of the developed model.

3.4.2. Marginal Service of Additional Tramcars. The AALRT tramcar has a capacity of 286 passengers. So, using the above-mentioned optimization methods, the research found the smallest number of tramcars required to alleviate congestion at a steady state. Figure 7 depicts the average percentage of passengers served per hour as a function of the number of tramcars deployed in the morning and afternoon shift simulations. Remarkably, the figure shows that adding a few more tramcars could significantly increase the average number of passengers served within an hour. The slope of the graph represents the rate of increase of the service with additional tramcar. In terms of the percentage of service provided, it may make sense to increase the number of tramcars operating until the marginal benefit of adding another tramcar begins to diminish, which occurs when the percentage of passengers served within an hour reaches 100%.

3.5. Future Performance of AALRT. Rail infrastructure is a large and costly investment; therefore, infrastructure managers should manage the infrastructure properly to achieve the aim of the project. Once the railway line is constructed it should be managed efficiently. The rising demand for public transportation in metro areas has a significant impact on the provided service. To have an efficient management system the infrastructure manager should know the excepted demand during the railway's lifetime.

3.5.1. Passenger Forecast. The four-step travel model is most commonly used to forecast passenger flow. The social, economic, population, traffic environment, and tram conditions all have an impact on the increase in passenger flow.

Table 3: Tramcar arrivals per hour with corresponding reductions in waiting time and congestion.

Corridor	Directions	Peak hours	Station	Average tramcar existing	Waiting time of passengers after adding one single or double tramcar	Waiting time of passengers after adding one tramcar	Waiting time of passengers after adding two tramcars	Percentage improvement of waiting time after adding one tramcar	Percentage improvement of waiting time after adding two tramcars	Percentage reduction of congestion by adding one tramcar	Percentage reduction of congestion by adding two tramcars
E-W	E-W	7–9 AM	Haya Hulet 1	4.18	14.37	11.59	9.71	19.35	32.43	29	88
	W-E	4–6 PM	Megenagna	4.30	13.95	11.32	9.52	18.85	31.76	42	99
N-S	S-N	7–9 AM	Legehar	4.20	14.29	11.54	9.68	19.24	32.26	46	99
	N-S	4–6 PM	Legehar	4.08	14.72	11.82	9.88	19.7	32.88	42	99

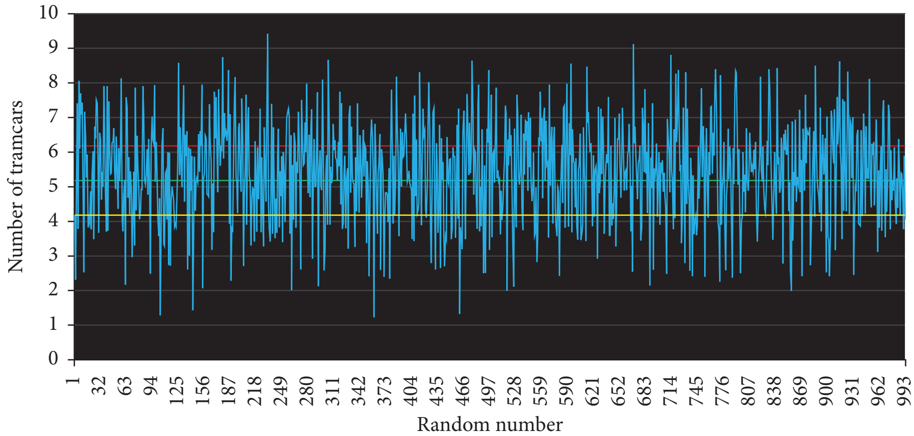

FIGURE 6: Simulation output and optimization solution at Haya Hulet 1 station, in the West to East direction, and in the afternoon shift.

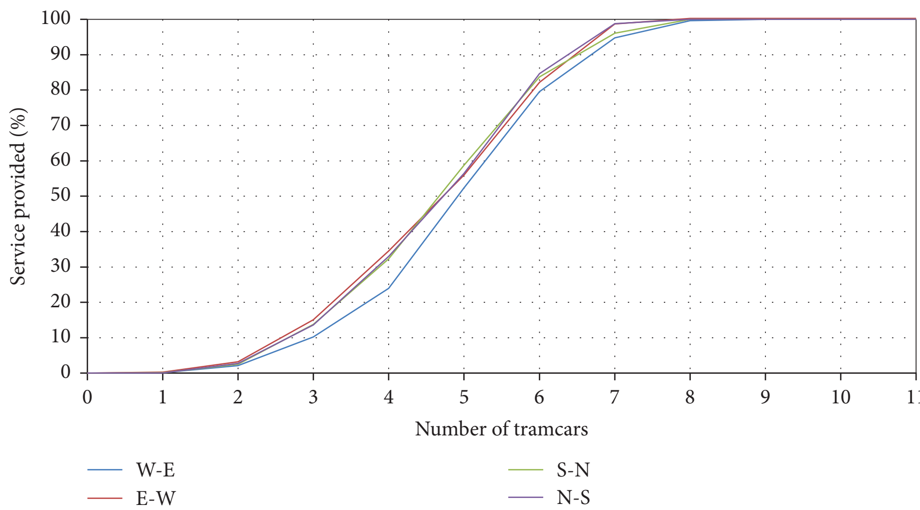

FIGURE 7: Marginal service provided by adding extra tramcar in both corridors and directions.

It can be difficult in developing nations to obtain the information required to employ the four-step travel model, which affects an increase in passenger flow. The population growth rate is a relevant factor in such a circumstance.

Population increase has a positive impact on trip flow. The population growth rate is used to determine the best way to predict passenger flow, taking into account the data collected regarding people's movements in each station along both corridors.

Population growth rates are based on the urban growth rates of Addis Ababa city as predicted by the Central Statistical Agency. Since the growth rates of passenger number are affected by population growth, so the growth factor is given as follows:

$$\mathrm{f}_{\mathrm{j+1}} = \frac{\left(pop_{j+1} - pop_j\right)}{pop_j} * 100, \tag{2}$$

where; f_{j+1} = growth factor, pop_{j+1} = population at $j+1$ year, pop_j = population at j year.

But, the approach used to forecast the AALRTs demand is based on a 3.8% of population growth in Addis Ababa city. By using the number of passengers per day by 2021 which was collected from the field, future passenger number at the end of 2026, 2031, 2036, 2041, and 2047 was calculated by the following equation.

$$T_{j+1} = f_{j+1} * T_j, \tag{3}$$

where; T_{j+1} = passenger number at $j+1$ year, f_{j+1} = growth factor, T_j = passenger number at j Year.

3.5.2. Summary of Future Performance of AALRT. As indicated in Table 4, adding one double tramcar per five-year interval can improve waiting time and congestion of AALRT. Furthermore, for the year 2047, adding six double tram cars and replacing the existing single tram cars with double tramcars will increase the system's capacity to eight double tramcars, reducing AALRT congestion 77% and waiting time up to 95%. Conclusively, the new model indicates the company can improve the service by increasing the number of tramcars per hour and replacing single tramcars with double tramcars up to 2047 without expansion of the infrastructure.

Table 4: Summary of tramcar arrivals per hour with corresponding reductions in waiting time and congestion in both corridors and directions at the end of specified years.

Year of services (at the end of)			2026		2031		2036		2041		2047	
			Percentage improvement of. . .									
Corridor	Direction	Station	Waiting time after adding 2 double tramcars	Congestion after adding 2 double tramcars	Waiting time after adding 3 double tramcars	Congestion after adding 3 double tramcars	Waiting time after adding 4 double tramcars	Congestion after adding 4 double tramcars	Waiting time after adding 5 double tramcars	Congestion after adding 5 double tramcars	Waiting time after adding 6 double tramcars	Congestion after adding 6 double tramcars
E-W	E-W	Haya Hulet 1	32.38	97	32.43	97	42.82	97	42.82	90	48.92	68
	W-E	Megenagna	31.73	100	31.76	100	41.08	99	41.08	94	48.17	75
N-S	S-N	Legehar	32.26	99	32.26	98	41.71	100	41.71	91	48.78	74
	N-S	Legehar	32.90	100	32.88	99	42.39	100	42.39	95	95	77

4. Conclusions

In this paper, an assessment of the current and future performance of the Addis Ababa Light Railway Transit service using mathematical modeling is done. Based on the analysis and findings of AALRT on most congested metro stations in both corridors and directions, the following conclusions have been summarized [23].

(i) At specified peak hours, the Addis Ababa Light Railway Transit service is observed to be congested in all corridors and directions.

(ii) A new optimization model is developed based on the optimization of the capacity of the service, the waiting time of the service, and the cost of the service.

(iii) As per optimization of the service's capacity, adding two additional tramcars can reduce congestion by 88% in the E-W direction and 99% in the W-E, S-N, and N-S directions.

(iv) The optimum waiting time of the current AALRT is 9.52 minutes from the existing 14.33, which can be achieved by adding two single more tramcars.

(v) This optimum waiting time decreases the waiting time of passengers by 4.66, 4.43, 4.61, and 4.84 minutes in the E-W, W-E, S-N, and N-S directions, respectively.

(vi) Based on the optimization of the waiting time of the service adding two single more tramcars can decrease the waiting time by 32.43, 31.76, 32.26, and 32.88% in the E-W, W-E, S-N, and N-S directions, respectively.

(vii) The findings revealed that improving the system's future performance by adding one double tramcar every five years can reduce AALRT waiting times and congestion.

(viii) Furthermore, for the year 2047, adding six double tram cars and replacing the existing single tram cars with double tramcars will increase the system's capacity to eight double tramcars, reducing AALRT congestion by 77% and waiting time up to 7.23 minutes.

Conclusively, the new model indicates the company can improve the service by increasing the number of tramcars per hour and replacing single tramcars with double tramcars up to 2047 without expansion of the infrastructure. The improvement through optimization would enhance customer satisfaction by decreasing waiting times and passenger congestion.

Data Availability

The data used to support the findings of this study can be obtained from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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References

[1] D. R. Mohapatra, *An Economic Analysis of Light Rail Transit in Addia Ababa Ethiopia*Amity Univesity, Ethiopia, 2019.

[2] W. Taddesse, *Assessing & Quantifying the Level of Traffic Congestion at Major Intersections in Addis Ababa*, Addis Ababa Institute of Technology, School of Civil and Environmental Engineeringe in Road & Transport Engineering, Addis Ababa, Ababa, 2011.

[3] K. Prah, A. Keshavarzsaleh, T. Kramberger, B. Jereb, and D. Dragan, "Optimal Bus stops' allocation: a school Bus routing problem with respect to terrain elevation," *Logistics & Sustainable Transport*, vol. 9, no. 2, pp. 1–15, 2018.

[4] K. Seong and Y. Choong, "Simulation modelling for evaluating performance of commuter system with Arena," *J. Qual. Meas. Anal.,* vol. 11, no. 2, pp. 47–60, 2015.

[5] T. Mesfin, *Evaluating Quality of Service on Public Bus Transportation and Improvement Strategy in Addis Ababa: (A Case Study on Sheger Mass Transport Enterprise)*, Addis Ababa Institute of Technology, School of Civil and Environmental Engineering, Addis Ababa, Ethiopia, 2018.

[6] S. D. Stoilova and V. V. Stoev, "Methodology of transport scheme selection for metro trains using a combined simulation-optimization model," *Promet - Traffic & Transportation*, vol. 29, no. 1, pp. 23–33, 2017.

[7] S. P. V. Mala, "Minimization of traffic congestion by using queuing theory," *Int. J. Sci. Technol. Res.,* vol. 8, no. 10, pp. 532–541, 2019.

[8] A. Zegeye, A. Worku, D. Tefera, M. Getu, and Y. Sileshi, *Introduction to research methods*, Graduate Studies and Research Office Addis Ababa University, Ethiopia, 2009.

[9] A. Sharma and P. Bakul Barua, "Application of queuing theory in a small enterprise," *International Journal of Engineering Trends and Technology*, vol. 27, no. 2, pp. 105–110, 2015.

[10] R. Mehandiratta, "Applications of queuing theory in health care," *Int. J. Comput. Bus*, vol. 2, no. 2, 2011.

[11] A. Nafees, *Queuing Theory and It's Aplication: Analysis of the Sales Checkout Operation in ICA Supermarket*Beijing China, 2007, http://www.statistics.du.se/essays/D07E.

[12] X. y. Xu, J. Liu, H. y. Li, and J. Q. Hu, "Analysis of subway station capacity with the use of queueing theory," *Transportation Research Part C: Emerging Technologies*, vol. 38, pp. 28–43, 2014.

[13] D. Selvapandian, J. Ravi, J. Mohan, H. Sabareesh, and G. Sathish Kumar, "Application of Queueing theory to Salem railway ticket counters," *Int. J. Stat. Appl. Math.,* vol. 3, no. 3, pp. 203–207, 2018.

[14] M. Marsudi and H. Shafeek, "The application of queuing theory in multi-stage production line," *Int. Conf. Ind. Eng. Oper. Manag*, vol. 8, no. –13, 2014.

[15] A. Hasan, N. R. Sahoo, A. Ghosh, and K. N. Jha, "A queuing model to improve the utilization of concreting equipment," in

Proceedings of the 23rd International Symposium on Advancement of Construction Management and Real Estate, pp. 992–1002, NY China, September 2021.
[16] C. Chen and J. S. Arthur, "Optimal Call Center Staffing via Simulation," *SIAM Undergraduate Research Online*, vol. 9, pp. 196–211, 2016.
[17] S. Prakash and A. Jokhan, "An optimal cane delivery scheduling using the Monte Carlo method," *ATRF 2016 - Australas. Transp. Res. Forum 2016, Proc*, vol. 21, pp. 1–10, 2016.
[18] F. J. Joubert and L. Pretorius, "Using Monte Carlo simulation to create a ranked check list of risks in a portfolio of railway construction projects," *South African Journal of Industrial Engineering*, vol. 28, no. 2, 2017.
[19] U. Manuel, "Application of queuing theory to automated teller machine (ATM) facilities using monte-carlo simulation," *Int. J. Eng. Sci. Technol*, vol. 6, no. 4, 2014.
[20] J. Ringelberg, A. Johnson, M. Boehlje, M. Gunderson, and N. Daninger, *Modeling with @ RISK:A Tutorial Guide*Dept. of Agricultural Economics Purdue University, West Lafayette, 2016.
[21] W. D. Kelton, *Simulation Modeling And Analysis*, Arizona, Tucson, 1991.
[22] M. Aftabuzzaman, "Measuring traffic congestion- A critical review," in *Proceedings of the 30th Australas. Transp. Res. Forum*, China, February 2007, https://www.researchgate.net/publication/282780229%0AMeasuring.
[23] M. Moussa, J. Y. Ruwanpura, G. Jergeas, and T. Mohamed, "Hybrid simulation environment for construction projects: identification of system design criteria," *Journal of Construction Engineering*, vol. 2014, Article ID 847430, pp. 1-12, 2014.
[24] S. Hillier and J. Lieberman, *Advance Praise for Introduction to Operations Research*, Seventh ed edition, 2001.
[25] H. Tekle, *Investigation on the Performance of Train Timetable for the Case of Addis Ababa Light Rail Transit*, Addis Ababa Institute Of Technology School of Electrical and Computer Engineering, Ethiopia, 2016.