Sensitivity Analysis in a BRT System

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***Abstract*—Mobility investments have increased due to the inconvenience caused by delays, traffic jams, and accidents. The Bus Rapid Transit (BRT) System is presented as an alternative to improve public transportation, as it can provide results with shorter travel time and lower costs, compared to other urban transportation systems. However, evaluating a system such as BRT can be a complex task, so using analytical modeling can favor evaluation and improvement for planning, using performance metrics that can be calculated using these models. This work proposes a Stochastic Petri Net (SPN) model for BRT System performance evaluation, focusing on sensitivity analysis to identify key factors that may affect Mean System Size, Mean Queue Size, Mean Queue Time and Utilization. Scenarios based on the BRT System were created. The results show that, from the managerial point of view, the factor that most impacts on the chosen metrics is the interval between departures, which directly affects the formation of the queue, affecting more than the passenger's own arrival interval at the station or even the time of entry into the vehicle or the number of seats.**

I. Introduction

The public transport system presents itself as an essential component to the development of a country, however, in developing countries, they have faced several problems. The lack of funding restricts the investments needed to maintain and expand the existing public transport system, which leads to a number of problems such as accidents, environmental degradation, congestion, and overcrowding, increasing the need to ensure that public transport systems are safe, accessible, efficient and effective. [1]

Problems in public transportation led to a lack of user confidence, which caused many to stop using public transport and continue to use their private vehicles [2].

BRT Systems have gained worldwide popularity as they offer fast, green, secure and efficient services. In addition to that, the cost of a BRT project may be about one third of the cost of a rail transportation project. BRTS can provide quality performance with sufficient carrying capacity. [3]

This research began with Dantas (2018) [4], where hierarchical models are presented, using Continuous Time Markov Chain (CTMC) modeling techniques to evaluate metrics, such as performance and performability of BRT Systems. From this study, we developed an SPN model with higher complexity of evaluation, looking for metrics such as Mean Queue Time, Mean System Time, Mean System Size, Probability the user miss the bus, Utilization, and Throughput. Thus, in this paper will be made the evaluation of which aspects of the BRT System can generate more impact in the results of each metric described, using for this purpose the Sensitivity Analysis.

The remainder of the paper is organized as follows: Section II shows the most important research in and around the studied area; while, Section III introduces the fundamental concepts of BRT systems, Performance Evaluation, SPN and, Sensitive Analysis; Section IV shows the stages of development of this study; Section V presents the proposed architecture and discusses the models proposed for the paper; Section VI presents the studies and highlights the results; and Section VII draws some conclusions and indicates the direction of possible future work.

II. Related Works

In the perspective of modeling of Urban Transport Systems, [5] adopted the GIS methodology - Geographic Information System, which considers topographic and geographic aspects, to analyze aspects of space and time in public transport. In order to calculate travel times more accurately, what is called *Three Dimensional Vehicle Run Representation* was constructed. In this method the idea is to mount a transport model as a projection of streets, vehicles and train lines, and time would be the third dimension. In this way, it is possible to evaluate the physical aspect of the system and make inferences to the planning.

Already [6] make an assessment of the performance of bus routes considering the perspective of the service provider as well as the passengers. It develops an approach that allows the decision maker to optimize the allocation of resources in the transit network, but also to achieve goals for the environment where services are provided. It is based on Data Envelopment Analysis (DEA) to show the relationship between the provider and the consumer of the Transportation service, considering external factors such as noise pollution and gas emissions, as well as considering the investments required to operate the system. Through the DEA, the authors are able to show the relationship of cost minimization with transportation costs and the maximization of service coverage area, which would help decision makers to choose better alternatives for the System.

[7] present the urban transport process describing four main activities: network design, timetable, scheduling of vehicles and scheduling of the employees who work in the system.

They describe the problem of the article as being about the integration of frequency and time of departure, where both are subactivities of the construction of the schedule, besides including multiple periods of planning and multiperiodic synchronization, also the authors consider uncertainties in the demand and the travel time. The authors created a mathematical model that includes these characteristics, aiming at minimizing the total cost of the operation, maximizing the number of multi-period synchronizations between the routes and minimizing the total waiting time of the passengers. The SAugmecon method is used to solve the scheduling problem, in addition, it is presented the comparison of this problem with the uncertainty about the demand and the uncertainty about the demand and the travel time. This model allows multiperiod planning and the implementation of multiperiod synchronization.

The present work offers an approach different from those described above. Here, the system modeling is done in SPN. Performance metrics are developed for system evaluation, such as Mean Queue Time, Mean System Size, Mean Queue Size, and System Utilization. This work differs from others in the literature, by performing a Sensitivity Analysis for the parameters that involve the BRT System in each chosen metric, becoming, therefore, relevant for the planning of these types of systems.

III. Fundamental Concepts

This section presents a summary of the concepts necessary for understanding this work and also provides an overview of the performance model in BRT systems.

A. Performance Evaluation

Performance assessment is required at every stage of the life cycle of a system, including its design, manufacturing, sale/purchase, use, upgrade, and so on. It is required when a system administrator wants to compare a number of systems and wants to decide which is best for a given set of applications. [8]

The three performance assessment techniques are analytical modeling, simulation, and measurement. The key consideration in deciding the evaluation technique is the phase of the life cycle in which the system is. [8]

Techniques based on modeling can be solved both analytically and by simulation. The analytical models use closed formulas or a set of the system of equations to describe the behavior of a system. The metrics of interest can be provided by means of the solution of closed formulas or the exact or approximate solution of a set of the system of equations provided by numerical mathematical algorithms [9].

B. Stochastic Petri Nets

Over the years, the study of Petri Nets has brought new possibilities with variations of the original model, such as timed, stochastic, high-level and object-oriented networks, which occurred because of the need for adaptability and the different characteristics and problems demands

In this study, we opted for the use of Stochastic Petri nets (SNPs) that add time to PN formalism and can be used for performance modeling and dependability. The time associated with the SPNs are associated with the transitions and are exponentially distributed, when the timed transitions, and zero, when the immediate transition [10].

The SPNs offer the possibility of joining the Petri Nets formalism ability to describe synchronization and concurrency with a stochastic model, allowing the description of a dynamic behavior in the modeling of performance and system dependability [11].

C. Sensitivity Analysis

According to [12], the sensitivity analysis is considered a strategy to evaluate the variation of the input parameters of the system and to identify how much these variations can interfere in the outputs of this system, in order to identify criticality points and promote system improvements.

Sensitivity analysis is an important stage in planning and also in the decision-making process since its purpose is: a) to make better decisions; b) define which estimated data must be deepened before the decision is made, and c) focus on critical elements during the implementation process of decisions. [13]

The sensitivity analysis will be carried out by the evaluation of the model through the scripted language of the software ®Mercury [14], which allows both the creation of the model and its analysis.

D. BRT System

In [15] the main characteristics of systems such as BRT are described: 1. Segregated bus routes; 2. fast boarding and disembarkation; 3. Cleaning, security, and comfort at stations and terminals; 4. efficient tariff collection (prior to shipment); 5. effective licensing and regulation regimes for bus operators; 6. Clear and visible signaling and presentation of information in real time; 7. Priority in traffic crossings; 8. Modal integration in stations and terminals; 9. vehicle cleaning technologies; 10. sophisticated marketing identity; and, 11. Excellence in customer service.

The BRT system consists of its central elements, which can be described as the routes used, the way stations and vehicles are presented, the charging system, the Intelligent Transport Systems, which are based on the creation of intelligent traffic lights, in addition to the planning and operation of the BRT Service itself. The elements described point to the possibility of the BRT System Performance analysis, which brings with it the need to create performance attributes and metrics. From the Performance System, we proceed to the Benefits System, which as in a cycle can also be the generator of all the need for the creation and implementation of a system such as BRT. [16].

The BRT is a fast transit system of buses that does not depend on traffic to reach the destination, since it is an exclusive route. This transportation system considers four specific performance metrics: Mobility (refers to the ability of the transportation system to facilitate efficient movement of people and goods); Reliability (refers to the ability of system users to predict the amount of time it takes to make a particular trip); Accessibility (refers to the ability of the transport system to connect people to desired destinations through spatial analysis of the residential population, employment centers, and other service or leisure opportunities); and Security (refers to the ability of system users to reach their destination safely on any trip). [17]

These characteristics differentiate BRT from other urban passenger transport systems since they can guarantee the customers' confidence, safety, mobility, and availability, in fact achieving dependability and the best performance.

IV. Methodology

One of the first tasks in a study is to determine the goals and how they may be reached. To evaluate the behavior of any system, it is necessary to understand and define the parameters to be evaluated; the considered resources should be important to the analysis and should help complete the objectives. After listing the important resources, a determination can be made as to a way to obtain the needed information [18].

For that, modeling strategies and analytical models were defined, seeking to evaluate the behavior of a BRT System under the perspective of performance evaluation. Finally, scenarios were constructed to evaluate the models, and from these, the Sensitivity Analysis was developed, to determine which factors most impact the results of the metrics studied. The figure **??** shows a flowchart that summarizes the strategy used in this paper.

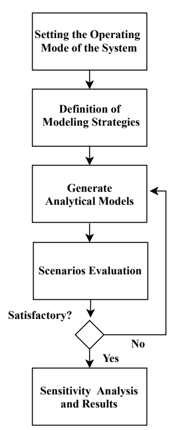


Fig. 1: Organization of the study.

Setting the Operating Mode of the System: Identifies the perspective of the system operation and defines the factors that will be considered in the operation of the BRT Systems. This is the main point of the work because it depends on the definition of the point of view that the work will address, in this case, the factors will be seen from the perspective of the system managers, considering the propagation of the decisions to the users. Defining the operational mode is what enables the development of the work;

Definition of Modeling Strategies: Identify the strategy that best suits the BRT System modeling for performance analysis. At this point, it is necessary to know the metrics to be evaluated to construct a model that better captures the result of these metrics. The chosen metrics were Mean Queue Time, Mean Queue Size, Mean Sytem Size and Utilization, so the chosen modeling strategy was SPN;

Generate analytical models: generation of performance models. In this step, the model will be effectively constructed, considering the metrics to be used and the expected results;

Scenario Evaluation: This stage of the work is the construction of scenarios and the numerical evaluation of performance. In this stage, the possibilities will be determined for scenarios that may represent the reality of some cities that will serve as a case study;

Sensitivity Analysis and Results: At this point, the factors that most impact the results of the chosen metrics will be presented, and the factors that should be considered in the evaluation are indicated.

V. SPN Model

The SPN model depicted in Figure 2 was conducted to evaluate the desired metrics. For better understanding, we separated it in three blocks, which are represented as: 1 (green) shows the Central Station, 2 (red) representing intermediate stations and 3 (blue) representing the Final Station. We emphasize that blocks 1 and 3 will be individual, and block 2 can be replicated according to the number of stations in the BRT System.

To evaluate the model, it is important to be familiar with the description of each transition, which will be presented in Table I. Considering that in this model, many of the arcs assume values other than 1, as it has associated probabilities of landing at the stations, we will also present the descriptions of weights of the arcs (Table II).

Block 1, in its upper part, represents the Central Station, Place **#A_CS** represents the arrival of the passenger, having a marking token in this place. The **T_ACS** Transition represents the interval between passenger arrivals at the station, which will be fired whenever it is enabled, consuming a token and depositing it in place of **#I_CS**, which represents the passenger's entry into the station. The **TI_CS** Immediate Transition is enabled if there is a token in places **#I_CS** and **#B_CS**, that represent the capacity of the station, i.e., the passenger queue limit. The shooting of **TI_CS** transition deposits a token to place **#A_CS**, representing that there will be the arrival of another passenger, with a token being deposited in place **#Q_CS**, where the passenger will be in the queue, limited to the capacity defined by the variable SC in place **#B_CS**. The passenger will leave the station and enter the bus in the **T_IB** Transition shot, which counts the time of entry of each passenger in the vehicle, represented as a single server. However, this transition is enabled if there is also a token in Place **#B_P_SC**. To have a token in this place, it is necessary that the vehicle has entered the route. For this, Place **#Buffer_Bus**, that represents the number of vehicles available for the System, must have a value other than 0; that is, the variable **bb**, that represents the number of vehicles, must be

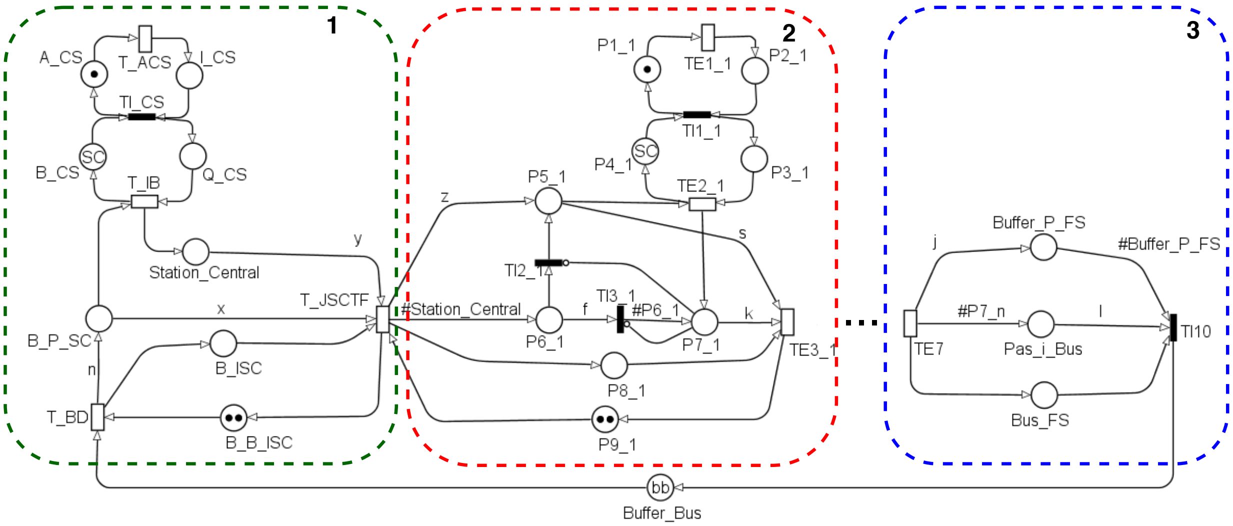


Fig. 2: SPN model of the BRT System.

Transition	Type	Server Type	Time	Weight	Priority
T_ACS	Exponential	Single Server	Passenger-to-station arrival interval		
TI_CS	Immediate			1	1
T_IB	Exponential	Single Server	Time for each passenger to access the vehicle		
T_BD	Exponential	Single Server	Vehicle departure interval (Headways)		
T_JSCTF	Exponential	Single Server	Travel time from one station to another		
TI2_1	Immediate			The probability that the passenger gets off the bus at the station.	1
TI3_1	Immediate			Probability of keep going	1
TE1_1	Exponential	Single Server	Passenger-to-station arrival interval		
TI1_1	Immediate			1	1
TE2_1	Exponential	Single Server	Time for each passenger to access the vehicle		
TE3_1	Exponential	Single Server	Travel time from one station to another		
TE7	Exponential	Single Server	Travel time from one station to another		
TI10	Immediate			1	1

TABLE I: Transitions from the SPN Model.

Arc	Weight
x	IF(#B_ISC>1):((#B_P_SC)-n)ELSE(#B_P_SC)
n	Number of assents on the bus
y	IF(#Station_Central>=1):(#Station_Central)ELSE(0);
z	IF(#B_ISC>1):((#B_P_SC)-50)ELSE(#B_P_SC);
f	IF(#P6_1>=1):(#P6_1)ELSE(1);
s	IF(#P8_1>1):((#P5_1)-50)ELSE(#P5_1);
k	IF(#P7_1>=1):(#P7_1)ELSE(0);
j	IF(#P8_5>1):((#P5_5)-50)ELSE(#P5_5)
l	IF(#Buffer_P_FS>=1):(#Buffer_P_FS)ELSE(1);

TABLE II: Weights of the Arcs of the Model SPN.

greater than or equal to 1 in its initial marking. This is due to the fact that this value enables the **T_BD** transition to be triggered, which will deposit in Place **#B_P_SC** the number of tokens determined by the weight of arc n. Variable n represents the capacity of the vehicle, which will be the seats available for boarding passengers. Thus, if there are tokens in Place **#B_P_SC** and Place **#Q_CS**, the transition **T_IB** can be shot, which shall deposit those tokens in the **#Station_Central**, limited to the capacity of the vehicle, **#B_P_SC**, and the number of passengers in the queue, **#Q_CS**. Place Central Station represents the number of passengers that are inside the vehicle.

In turn, place **#B_ISC** represents that the vehicle is at the station. This place will have tokens deposited by the shot of the transition **T_BO**, which will be enabled if there are tokens in places **#Buffer_Bus** and **#B_B_ISC**. Place **#B_B_ISC** represents the number of vehicles capable of stopping at the station. In the case of BRT stations, this limit is restricted to two vehicles per station, so the initial marking of the model is 2 tokens in Place **#B_B_ISC** and each shot of the T_BO a token is consumed and deposited in Place **#B_ISC**.

The transition **T_JSCTF** represents the travel time from **#Central_Station** to **#Station_1**. The shot transition **T_JSCTF** precedes a necessary condition for it to be enabled, which is the need to have at least one bus at the station; i.e., that Place **#B_ISC** is larger or equal to 1. The transition is still fed by two arches, the one coming from place **Central_Station**, that has weight **y** and represents the condition of consumption of all tokens of place **Central_Station**, in case there are tokens in this place; or it will have weight of consumption 0 if there is no passenger in the station, leaving the bus free to proceed without any passengers. The other arc that enables the **T_JSCTF** transition precedes place **#B_P_SC**, which has weight **x**. This variable represents that if place **#B_ISC** has more than one token, the weight of the arc will be **#B_P_SC** (the number of seats remaining in the vehicle, since some vacancies may have been subtracted by **T_IB**), subtracted from n, which is the capacity of a vehicle. This is due to the fact that displacement occurs from one vehicle at a time, with this condition limiting the number of spaces that can be occupied per vehicle. If there is only one token in **#B_ISC** the weight of the arc will be equal to the number of tokens of **#B_P_SC**; that is, all vacancies will be subtracted by the shot of the transition, which represents the passage of the vehicle to the next station, in this case, Block 2.

Block 2 (red) represents an intermediate station of a BRT System. The fire of the **T_JSCTF** transition will consume the tokens described and deposit them in the following places: In **#P5_1**, which represents the number of seats available in the vehicle; the arc connecting the transition to the place will have weight z, describing that the number of available seats in the transition will be conditioned to place **#B_ISC**; and, if this place is larger than 1 the weight of the arc will be (**#B_P_CS**-n), since it will have more than one vehicle. In turn, n represents the seats of a vehicle, and, if it is less than or equal to 1, it will be the very amount of **#B_P_SC**. Another place that will receive a token will be **#P8_1**, that given the weight of the arc, it will receive 1 token, representing the arrival of the vehicle the station. It is worth mentioning that the number of tokens of **#P8_1** is limited to the number of vacancies in the station, which is represented by **#P9_1**. The last place to receive tokens from the **T_JSCTF** transition will be **#P6_1**, which actually represents the number of passengers that have accessed the station through the vehicle, so much so that the weight of the arc connecting the transition to the place is determined by the amount tokens at place **#Central_Station**.

However, when the vehicle arrives at station $\#P6\_1$, there is the possibility of the passenger getting off the vehicle, which in this case is represented by the immediate transition **TI2_1**, that will have a weight associated with depending on the percentage of passengers disembarking at the station, or remaining in the vehicle, represented by the immediate transition **TI3_1**, which will also have an associated weight depending on the landing rates of the stations. For the immediate transitions **TI2_1** and **TI3_1**, there are associated inhibitory arcs, since for the construction of the model it was considered that the procedure must be to follow the landing order first and then the shipment. Firing **TI2_1** transition consumes tokens from place **#P6_1** and deposits them in place **#P5_1**, which represents the number of places available in the vehicle; i.e., the landing of the passengers will generate new vacancies in the vehicle. Firing **TI3_1** transition is preceded by the consumption of tokens of Place **#P6_1**, which will be represented by arc **f**, considering the consumption of all tokens of the place; that is, weight equal to **#P6_1**, which would deposit the same quantity in **#P7_1**, representing the passengers inside the vehicle at the station.

The arrival at the station in block 2 is represented similarly to Station Central: **#P1_1** represents the arrival of the passenger to the station, with a mark token in place; the **TE1_1** transition represents the passenger arrivals interval, which consumes the token of **#P1_1** and deposits it in **#P2_1**, representing the passenger's entry into the station. The Immediate Transition **TI1_1** is enabled if there is a token in places **#P2_1** and **#P4_1**, which is the capacity of the station queue; in this case, represented by variable **SC**. Thus, when the passenger arrives at the station and is in the queue, the transition will be triggered by consuming a token of the respective seats and depositing them in **#P3_1**, which represents the passengers at the station waiting for the vehicle.

Firing **TE2_1** transition is limited to the number of tokens in **#P5_1**, which represents the seats in the vehicle, and in **#P3_1**, the number of passengers in the queue. If enabled, the **TE2_1** transition will consume tokens of **#P3_1** and **#P5_1**, with the time associated with it determined by the average time each passenger takes to enter the vehicle. The **TE2_1** transition will deposit tokens in place **#P7_1**, which shows the number of passengers in the vehicle.

TE3_1 transition firing, which represents the time of travel between stations, denotes the consumption of three-place tokens: **P5_1**, where there will be the consumption of tokens defined by variable f. This variable represents that if there is more than one token in place **P5_1**, all will be consumed; otherwise, the arc will assume weight 1; **P7_1**, where there will be the consumption of tokens defined by the variable k, which represents that if the place **P7_1** is greater or equal to 1, the weight of the arc will be the number of tokens of the place, if 0, the weight of the arc will be 0; and, finally, **P8_1**, which has a weight of 1 and represents that the vehicle has moved to the next station.

The last block, 3, represents the final station. Firing Transition **TE** consumes the tokens of the places associated with the last station, Final Station, and deposits the token in those places: **#Buffer_P_FS**, which represents the number of free seats remaining in the vehicle at the end of the course, conditioned by the weight of arc **j**. Arc **j** is defined by the number of vehicles in the previous station $\#P8\_x$, where, if it is greater than 1, the weight of the arc will be the number of seats in the vehicle in the previous station minus the vehicle capacity n, $\#P5\_1 - n$. Otherwise, if it is less than or equal to 1, it will be the number of available vacancies, **#P5_1**;

#Bus_FS, which represents that the bus is at the Final Station, having deposited 1 token there. The immediate transition fire **TI10** is conditioned by the consumption of tokens of places: **#Buffer_P_FS**, from where all the tokens will be consumed since the vehicle will return to the garage, that is, all the vacancies will be available; **#Pas_I_Bus**, which will feed the transition with arc **l**, where in case the place has one or more tokens, it will be the total number of tokens to be consumed and, and if it is 0, it will have weight 1 to enable the transition. The transition fire deposits one token into Place **#Buffer_Bus**, which means that the vehicle is ready for use again.

From this model, it is possible to evaluate several metrics. However, in this paper, we chose the metrics Mean Queue Size, Mean Queue Time, Mean System Size and Utilization. From the definition of the metrics, the sensitivity analysis was performed in the model, verifying that factors more impact on the result of each metric.

VI. Sensitivity Analysis

Sensitivity analysis is an important planning tool, since it allows identifying the factors that most impact the system, identifying how this will affect the results sought.

In this paper, the sensitivity analysis corroborates the identification of the factors that cause the most impact on transportation systems, for which the model presented in Section V was used. The model is described in Figure 2, however, the sensitivity analysis will consider all the transitions that are in the model, where they are considered a central station and an end station, and five intermediate stations. To facilitate the reader's understanding, the table III describes the transitions presented in the model complete, highlighting what each represents.

The sensitivity analysis will be through the script language of the software ®Mercury, which allows both the creation of the model and its analysis.

TABLE III: Transitions to Sensitivity Analysis.

TRANS.	REPRESENTATION IN THE MODEL
ACS	Arrival interval of the passengers in the Central Station
T1_1	Arrival interval of the passengers in the Station 1
T1_2	Arrival interval of the passengers in the Station 2
T0	Arrival interval of the passengers in the Station 3
T3	Arrival interval of the passengers in the Station 4
T8	Arrival interval of the passengers in the Station 5
TIB	Interval for the passenger to enter the Vehicle at the Cent. St.
T2_1	Interval for the passenger to enter the Vehicle at the Station 1
T2_2	Interval for the passenger to enter the Vehicle at the Station 2
T1	Interval for the passenger to enter the Vehicle at the Station 3
T4	Interval for the passenger to enter the Vehicle at the Station 4
T6	Interval for the passenger to enter the Vehicle at the Station 5
TBD	Interval Between Bus Departures
TJSCTF	Time from Central Station to Station 1
T3_1	Time from Station 1 to Station 2
T3_2	Time from Station 2 to Station 3
T2	Time from Station 3 to Station 4
T5	Time from Station 4 to Station 5
T7	Time from Station 5 to Station Final Station

A. Sensitivity Analysis for the Mean System Size (MSS)

The Mean System Size represents the number of people who are in the BRT System, either in the vehicle or waiting at the station, that is, it represents the total numbers of people for each scenario. In order to visualize the results, the figure 3 was constructed, which presents the main factors in order of importance.

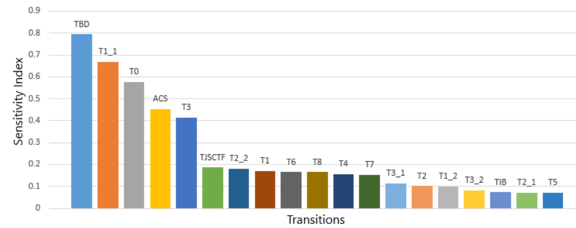


Fig. 3: Sensitivity Analysis for MSS.

In Figure 3 it is possible to identify that the transition that most impacts the model, is the **TBD** that represents the interval between bus departures. This factor points out that the starting interval interferes more directly in the system, that is, if it is a larger starting interval, more people will be in the systems, or waiting in the queues or traveling in the vehicles, if it is smaller the opposite.

It can also be highlighted the set of transitions **T1_1, T0, ACS e T3**, which represent the range of arrivals of the passengers to the stations, also has a strong influence on the Mean System Size, with emphasis for the entrance in Station 1 and Station 2, which present the highest sensitivity indexes, meaning that one must pay attention to these stations, or even create alternatives to minimize the impact on the System.

B. Sensitivity Analysis for Mean Queue Size (MQS)

The Mean Queue Size (MQS) represents the number of Passengers waiting to access the vehicle. For transport system planners the minimization of the queue presents itself as an important factor, since besides interfering in the image that of what the System Represents for society, it insures in costs for the own system and passengers.

In an Analysis of the factors that most impact the Mean Queue Size, confirming what was presented in the previous section VI-A, the transition that has the greatest impact on the queue is **TBD**, as can be seen in Figure 4.

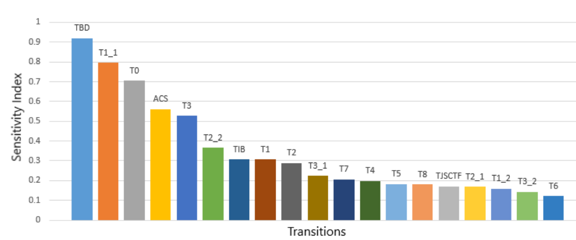


Fig. 4: Sensitivity Analysis for MQS.

The Figure 4 shows that for the Queue Size the factors that most impact are: the bus departure interval (**TBD**), the interval between arrivals of passengers in Stations 1 and 3 (**T1_1**, **T0**), and the arrival interval to Central Station (**ACS**). In a comparison with the previous subsection (VI-A), the sensitivity index has a higher value, reaching, in the cases cited, more than 50 %, which shows the strong impact on the result for changes in these transitions. Thus, it is necessary to pay attention to these factors, when it is sought to satisfy the needs of the passengers, who are the ones that will be impacted by the size of the queue.

C. Sensitivity Analysis for Mean Queue Time (MQT)

Another factor evaluated by the model, through the Script for evaluation of performance metrics in transport systems, was the impact of the factors in the Mean Queue Time, which has its results presented in Figure 5.

The Mean Queue Time represents, on an observation of the system, the average time each passenger is waiting to board the vehicle. Thus, the relationship of queuing time is a very interesting metric for evaluation since it directly impacts the image that the BRT System can generate for users since long queues cause discomfort and inconvenience for those who wait.

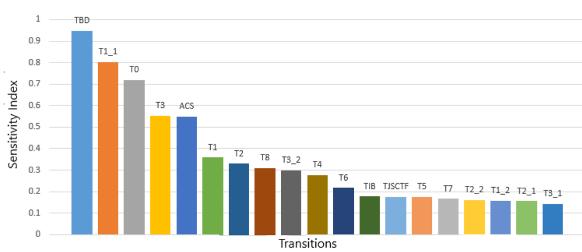


Fig. 5: Sensitivity Analysis for MQT.

It is possible to notice that in the Figure 5 the most important factors for the system, represented by the Transitions T **TBD, T1_1, and T0**, respectively, represent the interval between departures of vehicles, arrivals intervals at station 1 and station 3. However, it is important to highlight the transition **T3**, which represents the arrival interval to Station 4, which theoretically is at the end of the route, however, at this station, still, there is a high probability that the passenger will not board the vehicle. In order to correct and minimize the waiting time of the passengers, the managers can think of alternatives such as mini-routes implantation inside the system, contemplating only the stations with greater demand and consequently, queue and wait, which could bring gains in the image to the system.

D. Sensitivity Analysis for the Utilization of the BRT System

When considering the level of use of the system, what is sought is to provide a balance between maximum utilization, with the minimum of resources, ensuring the service of the users in a satisfactory way, without grips or queues. Thus, we verified the factors that most impact on the utilization of the system, being evaluated station by season as each transition interferes in the result, shown in Figure 6.

In figure 6a, which presents the results for the Central Station, the predominant factor is the arrival interval of the passengers to the Central Station (**ACS**), which shows that at the beginning of the Route the passenger arrival time interferes more with the level of utilization than the vehicle departures interval (**TBD**), which until then has been shown to be the predominant factor of the system. This can occur because at the central station the passenger arrivals range is low, generating an accumulation of passengers already waiting for the vehicle.

Figure 6b shows the results for Station 1, where the sensitivity index for the Utilization metric indicates that the factors that most affect the result are the vehicle departures interval (**TBD**), in first place, followed by the arrival interval of the passengers to Central Station (**ACS**) and the arrival interval of the passengers to Station 1 (**T1**). These transitions are highlighted in front of the others, which prevails given the analysis being made in relation to Station 1, and until this station only the passengers of the Central Station and Station 1 are in the system, limited to the number of spaces in the vehicle.

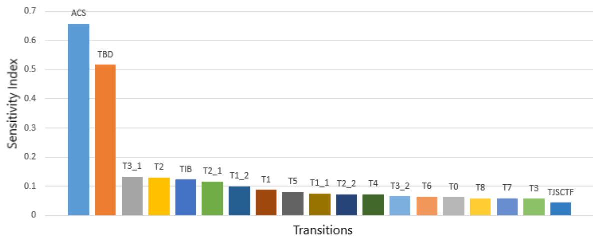
For Stations 2, 3, 4 and 5 (Figures 6c, 6d, 6e and 6f), three main factors remain in the following order: **TBD**, **t1_1** and **ACS**, respectively, vehicles departure interval, arrivals intervals to Station 1, and arrivals intervals to Central Station . This can happen due to the higher demands of arrivals in the first stations, thus, the system would reach a certain level of equilibrium in utilization from Station 2, with a little importance index of changing between the most important transitions during the route.

VII. Conclusion

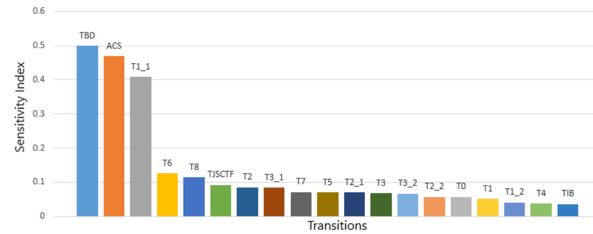
This paper addressed the fundamental factors involved in BRT systems, employing SPN model as a means to foster system analysis and improve the planning process, particularly with respect to the factors that should be most observed when performance. From the model, an analysis was made through the Script to evaluate performance metrics in transport systems, in ®Mercury software.

The results show that in a sensitivity analysis for the factors that most impact the performance of the BRT system, the headways as the preponderant factor, that is, in a system planning, even with good stations and even with vehicles with seats, if the departure interval is not adjusted with what the system requires, there will always be queues.

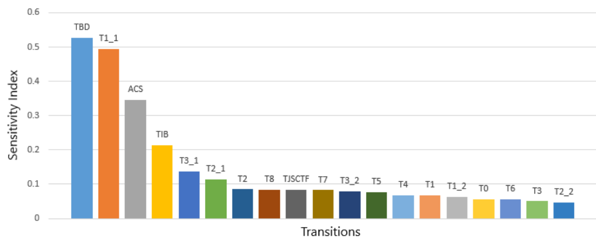
Thus, this study shows its relevance for anticipating to managers the possibilities of combining Headways that favor the system, without actually having to impact the system, since it is done through the use of the model. For future studies, other metrics, such as capacity, and, the cost factors can be studied and harnessed to ensure better prospects for planning BRT systems.



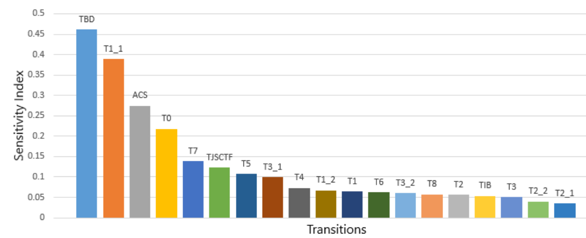
(a) Sensitivity Analysis for Utilization at Central Station.



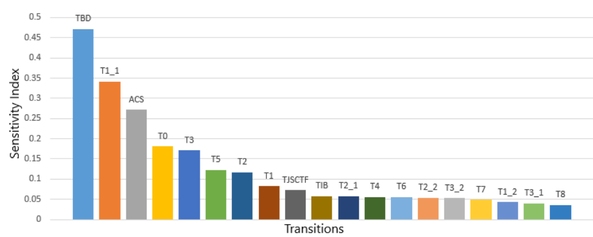
(b) Sensitivity Analysis for Utilization at Station 1.



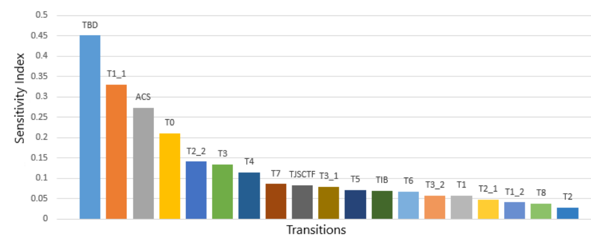
(c) Sensitivity Analysis for Utilization at Station 2.



(d) Sensitivity Analysis for Utilization at Station 3.



(e) Sensitivity Analysis for Utilization at Station 4.



(f) Sensitivity Analysis for Utilization at Station 5.

Fig. 6: Sensitivity Analysis for Utilization at BRT System.

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