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Quantitative Analysis of RFID based Vehicle Toll Collection System using UML and SPN

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Abstract: This paper focuses on the quantitative analysis of RFID based vehicle toll collection system. Since we conduct the quantitative analysis long before the implementation of the infrastructure, the approach is realized by the UML and SPN to capture the system dynamics and carry out multiple performance tests of the possible infrastructure. Thus, the performance tests ensure the installation of correct number of RFID vehicle toll collection booth in the entrance of a bridge or a highway so that the traffic congestion can be kept as minimal as possible as well as financial viability can be confirmed. We analyze the response time and throughput to know the maximum limit for the diverse number of arrival vehicles that is served by the different number of toll booths. This finally gives us a better understanding of the number of units necessary for toll collection to decrease the traffic congestion in a budget constraint manner.

Index Terms: Quantitative analysis, UML, RFID, SPN.

1. Introduction

Our quality of life is improving gradually and the role of automation in our daily life is increasing as well. Bangladesh is developing progressively, its road and transport system is also developing and as a result, the number of vehicles is increasing rapidly in urban area. As vehicles number is increasing gradually, the pressure on the toll collection booth is also escalating in a bridge or in a highway. It is a common phenomenon of huge traffic in a toll collection booth currently because toll collection is mostly done manually. Hence, this calls for an automated approach to replace today's manual toll collection system. As a result, we are mainly interested in developing Radio-Frequency Identification (RFID) based vehicle automated toll collection booth where the car will need a registered RFID tag and sufficient balance in their virtual wallet that can perform the toll collection in a faster manner. But lot of efforts have already been taken so far to introduce RFID based vehicle toll collection toll all over the world [1-7]. So, this development will not attract the scientific community any further instead conducting a quantitative analysis of the RFID based toll collection booth before development of the infrastructure will be more fascinating and viable issue where not much effort has been given. As the traffic condition in Bangladesh is very devastating, knowing the exact number toll collection booth is a must and that is required to minimize the traffic congestion at a manageable level by considering the arrival rate of the vehicle in the peak interval. It is not beneficiary to install vast number toll collection booth at certain location without performing proper analysis of the vehicle arrival frequency and execution time required of the toll collection booth. Moreover, this approach will ensure the optimal budget allocation in a developing country like Bangladesh to develop only the necessary infrastructure to maximize the benefit and refrain the government to increase the budget unnecessarily.

To gain the full benefit of our quantitative analysis we are performing the analysis task before implementing the system's infrastructure to make the prediction correctly. This will stipulate immense challenge to capture the toll collection system's behavior. To meet up this challenge, we implement a model-oriented method, where the system's behavioral attribute is detailed by Unified Modeling Language (UML), that is a generally used modeling specification language for long in software engineering domain [8]. UML offers a variety of diagrams which enables the delineation of the system behavioral attributes from various perspectives. UML collaboration is introduced here as the principal structural unit that specifies the system's behavioral attributes. Collaboration is an integral part of UML collaboration diagram which is utilized to define the association between collaboration roles. Collaboration roles are realized by the service components in this work. The structural properties of the service with amalgamation of the service components and the essential binding among them is specified using collaboration diagram as encapsulated building blocks which is a special and unique feature of this task. The block is defined as an encapsulated building block which means that the properties of the service component is contained in the block which later will be composed with other building blocks to reflect the service structural properties [9]. More specifically, the encapsulated building block enriched system definition facilitates the reusability of the self-contained block later to define the analogous service properties. It eventually, ensures the software development jobs simpler and quicker by canceling the starting of the development task from scratch and it vanishes the need for a developer to be skillful in every software engineering domain [10].

Service structural specification provided by the UML collaboration has the limitation of not being able to reveal the behavioral characteristic of the collaboration which is stated as encapsulated building blocks. This behavioral specification of collaboration is important to know in detail while converting the UML model into analytical model and conduct the quantitative analysis. Knowing the thorough functional characteristic of the service components will help to conduct the model conversion in an appropriate and error free manner. To facilitate this, UML activity has been applied to reveal the characteristics of encapsulated building blocks. More specifically, UML activity is utilized to define the internal behavioral aspect of the collaboration through activity compartment presented for individual collaboration role in the structural specification [10].

Structural specification of system using UML collaboration and behavioral specification using UML activity are utilized to accompaniment each other to reveal the detail behavioral aspect and coupling of the different events of the system and its components using collaborative building blocks [9]. To elaborate this specification in the finest level, call behavior actions are exploited. The call behavior actions inside a collaboration ultimately define the activity of a particular building block. Call behavior actions of a corresponding building block has been declared as a pin which refers to the activity parameter that is later utilized to glue with other building block to disclose the detail system's behavior. Pin will be labeled as a symbol or name as a part of the activity parameter to express them in the collaborative building block. Harmonization of the random logic among the building block activities and data transformation among them have been accomplished using pins. The pins are recognized both as input and output pins of the call behavior actions to couple the different events of the collaborative building block to reveal the behavioral aspect of the systems [11].

There are several alternatives that provide efficient analytical modeling and quantitative evaluation method such as Markov models, queuing networks, stochastic process algebras and stochastic petri net (SPN) [12]. Among all these, SPN model is our choice because of its UML activity like semantic which facilitates the model transformation process accurate, precise, and speedier. However, additional attractive features of SPN such as popular and easy semantics for describing and analyzing systems, modeling generalization and simplification, power of capturing the complex system behavior succinctly, capability of preserving the real architecture of the system, to provide necessary adjustment after having feedback from analytical model evaluation and the presence of analysis tools.

Lastly, the objective of the paper is to provide a quantitative analysis of the RFID based vehicle toll collection booth to know the exact number of booths required to keep the traffic congestion as minimal as possible and efficient allocation of budget by considering the arrival rate of vehicles and processing time required for the tool collection booth at a certain location. The paper is structured in the following manner: section 2 describes our research approach, section 3 defines the system overview, section 4 describes the result of the quantitative analysis and section 5 presents the conclusion with future aim.

2. Research Approach

A systematic and scientific research approach is necessary to produce realistic results which reveals the validation and verification of our research [10]. This approach should be formed with the methodology from the existing approach which will help to gain and disseminate new knowledges to the scientific community through this novel work. The scenario-driven research method is most suited research approach we are applying in our research because it is a comprehensive method to simulate the real phenomena in the necessary research setting, provide extensive description to reveal the circumstance, and to facilitate the quantitative analysis based on the realistic parameters of interest. Considering the scenario base research method our research approach is divided into the following 3 segments:

Scenario construction: To construct the scenario considering the requirements of our research we initiate a knowledge acquisition phase via performing extensive literature study of relevant thoughts. This study helps to decide about necessary assumptions, criteria, and constraints to resemble the real phenomena while building the scenario. The scenario should be formed in such a way that allows us to accomplish essential performance analysis precisely and correctly using realistic parameters.

Research Execution: When scenario construction will be accomplished a systematic approach will be followed to provide system specification considering the dynamics and interaction of the system components. The anticipated outcome of this systematic approach is the appropriate architectural design semantics of the RFID based toll collection system. This architectural semantics will be tested against the analytical model which is the output of the model transformation process in accordance with our research objective and goal.

Research Evaluation: Evaluation of this research is accomplished with automated tool-based assessment of the analytical model and determination of quantitative result which can provide indication regarding the design constraints and can be utilized to resolve any issue that might happen in the real scenario.

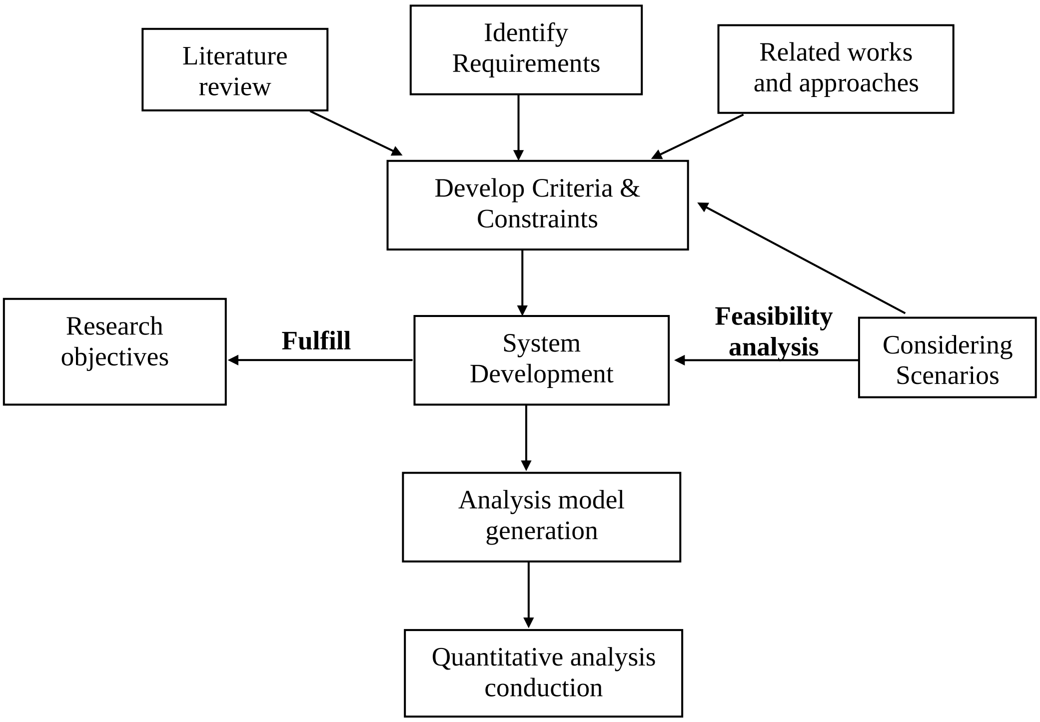

Fig.1. Research method demonstration

3. System Overview

As we are considering scenario driven approach to capture system dynamics and conduct quantitative analysis the detail scenario description is delineated which is shown in Fig. 2 [6]. A vehicle approaches the toll collection booth if the booth is vacant and ready to collect vehicle toll. After scanning the RFID tag of the car, the toll will be collected by the booth using online payment system. An entry of the payment will be recorded in the backend system and an acknowledgement will be directed to the vehicle owner through short message service (SMS).

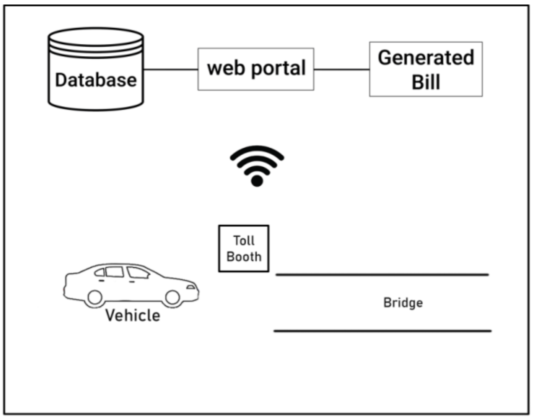

Fig.2. Sample scenario

3.1. UML based System Illustration

To capture the functional behavior of the system appropriately, we utilize the power of UML collaboration and activity which is explained as follows. UML collaboration diagram demonstrates the association and interaction between collaboration roles or objects. The collaboration diagram illustrates the high-level abstract representation of the operational behavior in an encapsulated means between classes and objects. So, for each operational behavior we create a collaboration diagram that later facilitates the faster and correct development of a service. UML diagram of our scenario shown in Fig. 3 consists of two collaboration roles which are *vehicle* and *toll booth* and the relationship between them is mentioned as *verification and process*. The collaboration just defines the structural information of our scenario.

Fig.3. Collaboration diagram of our system

To define the detailed behavior of the object of our system we focus on the UML activity. It represents actions or flow of control performed by the objects dynamically in a system. Activity diagrams are used in our work to elaborate and expand the behavior visually that is encapsulated in the collaboration demonstrated earlier. This visual representation illustrates the complex behavior such as sequential and concurrency nicely that facilities error free development of the system. Activity diagram of our system shown in Fig. 4 is delineated as follows: we create two partitions of our activity diagram for two objects illustrated in collaboration diagram. When a vehicle arrives in the toll collection booth it is reflected as a request message to the booth. RFID tag of the car will then be scanned by the tag reader placed in the booth. After scanning and verification is done appropriate amount is deducted from the car owner account or card using online payment system and acknowledge message is sent to the driver. Then next car will be treated by the booth in the same way to perform verification and processing of payment.

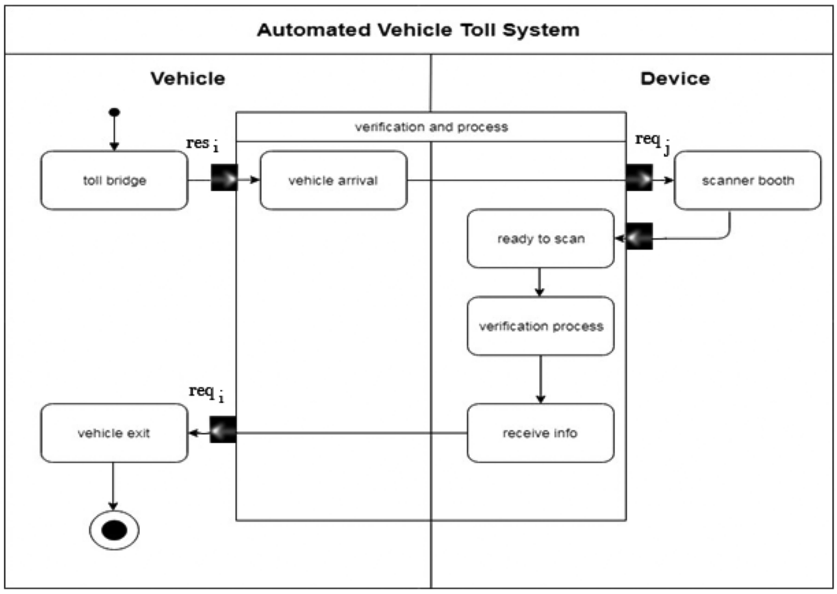

Fig.4. Activity diagram of our system

3.2. *Illustration of Analytical Model*

While UML syntax is utilized to delineate the functional behavior of the system, we need an efficient method to analyze the UML model to produce analytical results. Here, SPN model comes into action to play the role of conducting quantitative assessment. Hence, to conduct this quantitative assessment we call for an error free and quick approach for transforming the model which produces SPN model from UML syntax. The SPN model formed here is realized by the 5-tuple $\{\wp, \mathfrak{L}, \beta, \mathbb{N}, \mathbb{C}\}$ that can be demonstrated in the following manner [13]:

$\wp$ = Defines the number of places as a set
$\mathfrak{L}$ = Defines the number of transitions as a set
$\beta \subseteq \{\wp \times \mathfrak{L}\} \cup \{\mathfrak{L} \times \wp\}$ defines the number of the arc connecting $\wp$ and $\mathfrak{L}$
$\mathbb{N}: \beta \rightarrow \{1, 2, 3, \ldots.\}$ defines the multiplicity assigned to the arcs in β.
$\mathbb{C}: \wp \rightarrow \{0, 1, 2, \ldots.\}$ defines the marking that symbolizes the available tokens in each place $\wp$. The initial marking is represented as $\mathbb{C}_0$.

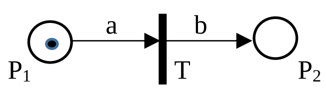

Fig.5. A SPN model

An example SPN model is shown in Fig. 5. Here, P_1 and P_2 are places. T is the transition. Input arc is a and the output arc is b. Initially, place P_1 has one token. After time elapse of the transition T, it fires, and token is deposited into place P_2 from place P_1.

3.3. Model Transformation

The model transformation process is challenging in a sense that its needs to be maintained consistency between the UML specification style and SPN model which calls for one-to-one mapping between the components of UML and SPN. Hence, to ensure this one-to-one mapping the model transformation process is realized by the model transformation rules. These model transformation rules ensure the consistency with corresponding specification styles of UML and SPN. This also offers an effectual, scalable, and automated methodology for managing the model transformation process [14]. The Rules for facilitating the model transformation process have been outlined as follows:

Rule 1: When we transfer a collaboration role into SPN model the tuple representation is given below (Fig.6):

$$\wp = \{p_i, d_i\}$$

$$\mathfrak{L} = \{do, exit\}$$

$$\beta = \{(p_i \times do) \cup (do \times d_i), (d_i \times exit) \cup (exit \times p_i)\}$$

$$\mathbb{N} = \{(p_i \times start) \to 1, (start \times b_i) \to 1, (b_i \times exit) \to 1, (exit \times a_i) \to 1\}$$

$$\mathbb{C}_0 = \{(p_i \to 1), (d_i \to 0)\}$$

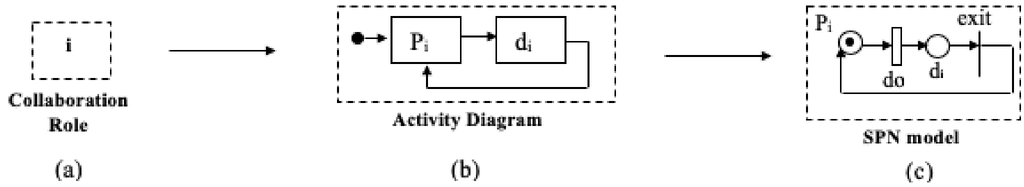

Fig.6. SPN model of a collaboration role

Rule 2: When we transfer a collaboration (where collaboration connects two collaboration roles) into SPN model the tuple is given below (Fig.7):

$$\wp = \{p_i, d_i, p_j, d_j\}$$

$$\mathfrak{L} = \{do_i,\ do_j, tr_{ij}\}$$

$$\beta = \{(p_i \times do_i) \cup (do_i \times d_i), (d_i \times tr_{ij}) \cup (tr_{ij} \times p_i), (p_j \times do_j) \cup (do_j \times d_j), (d_j \times tr_{ij}) \cup (tr_{ij} \times p_j)\}$$

$$\mathbb{N} = \{(p_i \times do_i), (do_i \times d_i), (d_i \times tr_{ij}), (tr_{ij} \times p_i), (p_j \times do_j), (do_j \times d_j), (d_j \times tr_{ij}), (tr_{ij} \times p_j) \to 1\}$$

$$\mathbb{C}_0 = \{(a_i \to 1), (b_i \to 0), (a_j \to 1), (b_j \to 0)\}$$

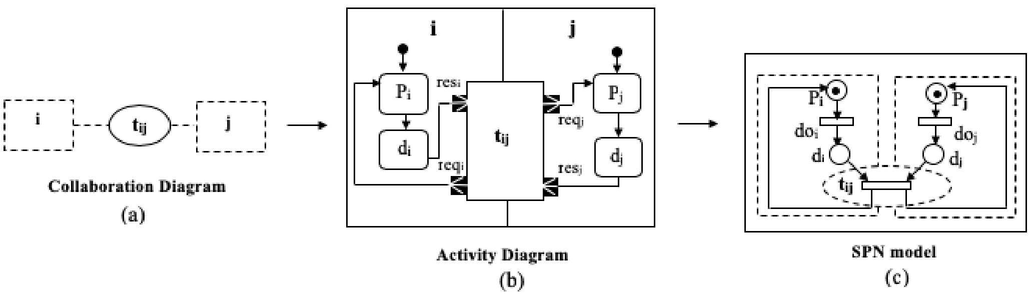

Fig.7. SPN model of a collaboration

Considering the collaboration diagram in Fig. 2, activity diagram in Fig. 3, and rules for model transformation the SPN model of our scenario is generated which is demonstrated in Fig. 8. There are two primary places in this SPN model which later branches to other places. Here place ‘a’ is representing the vehicle and place ‘b’ is representing the toll collection booth. Token in place ‘a’ represents the number of vehicle available in the system whereas token in place ‘b’ symbolizes the number of toll collection booth available in the system. With the enabling of the transition ‘t’ after some probabilistic delay transition ‘t’ fires which causes the withdrawing of one token from place ‘a’ and depositing of one token into place ‘c’. Same event happens with transition ‘u’, and place ‘b’, ‘d’. As soon as both places ‘c’ and ‘d’ get one token each, after some probabilistic delay transition ‘v’ fires and the tokens of both places ‘c’ and ‘d’ remove and deposit into place ‘a’ and ‘b’ which symbolizes the ending of the toll collection of the car that passes the toll booth.

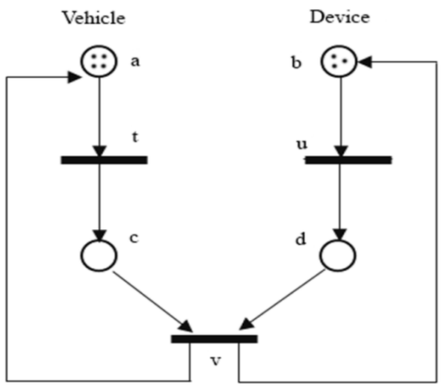

Fig.8. SPN model of our scenario

4. Result Analysis

As mentioned earlier, the efficiency of our approach is reflected by determining the exact number of toll collection booth necessary to minimize the traffic congestion in a budget friendly manner. This has been shown by achieving the quantitative analysis of our analytical model i.e., SPN. While performing the quantitative analysis, we conduct the throughput and response time analysis of the toll collection unit for serving certain number of vehicles in a particular time instance. Here, throughput is a measure of how many units of vehicle can be processed by our toll collection booth in a given amount of time. Response time is the amount of time from the moment that a car enters the booth until the time that the toll booth indicates the toll collection has completed. Both are related measures of system productivity which includes the speed with which some specific tasks can be completed in a particular time. In stable condition, throughput and response time increase as the numbers of service request increase. But when the large number of service request arrives which is beyond the scope the system’s capacity the throughput and response time become saturated which means no further increase of the system productivity is achievable. So, the quantitative of analysis of our SPN model determines exact number of toll booth necessary for which throughput and response time of the system become saturated even after number of vehicle arrival increases in the system [15].

In Fig. 9 the throughout calculation of our system has been demonstrated. X axis represents the number of arrival vehicle in a specific arrival rate. Y axis represents the number toll collection booth. We consider 1, 3, 5, 7, and 10 toll collection booths to see the changes in throughput for the arrival of different number of vehicles in the system. When there is only 1 toll collection booth available in the system throughput of the system increases linearly. For 3 toll collection booths, it shows much improvement in throughput comparing with single unit. But for 5, 7, and 10 toll collection booths, it only shows a very small increment in throughput initially but reaching a constant state finally comparing with 1 or 3 units. Thus, we can reach a conclusion that installing 3 to 4 units of toll collection both will minimize the traffic congestion but installing of extra unit will just increase the budget without providing any benefit in minimizing the traffic congestion. Same discussion is applicable for the response time calculation of our system which is shown in Fig. 10.

The throughput and response time calculation of the different numbers of toll collection booth reveals the tendency of the system in heavy traffic situations for diverse arrival rate of the vehicles. So unnecessary installation of the toll booth can be predicted for any heavy traffic location. This in the long run will help taking the decision of budget allocation for toll booth installation. This decision-making process covers a good range of non-functional properties of the system such as performance, cost, dependability etc. parameters. In this way, the research objective of this task is accomplished, and clear novelty is exposed.

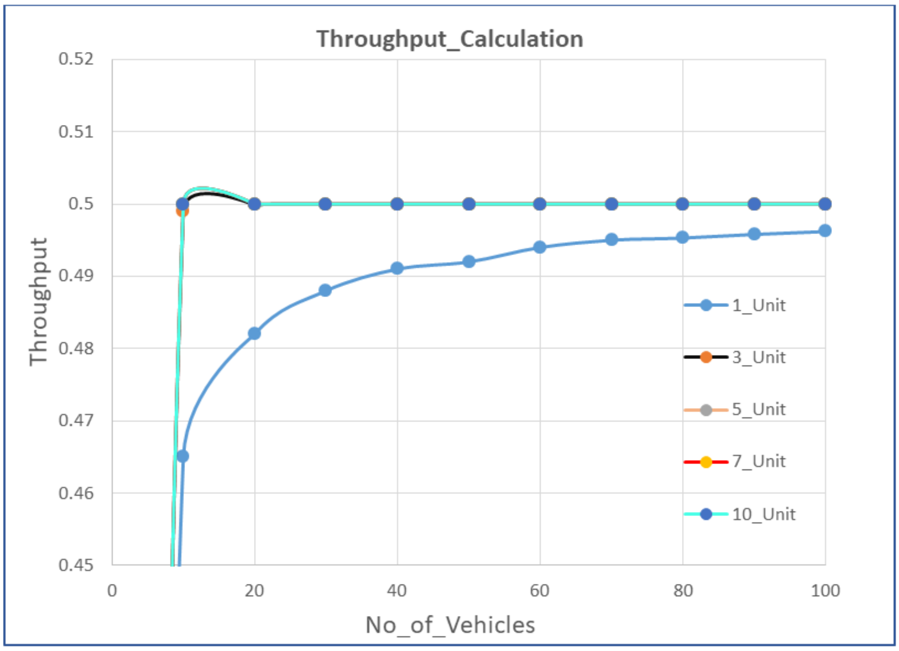

Fig.9. Throughput result of our example scenario

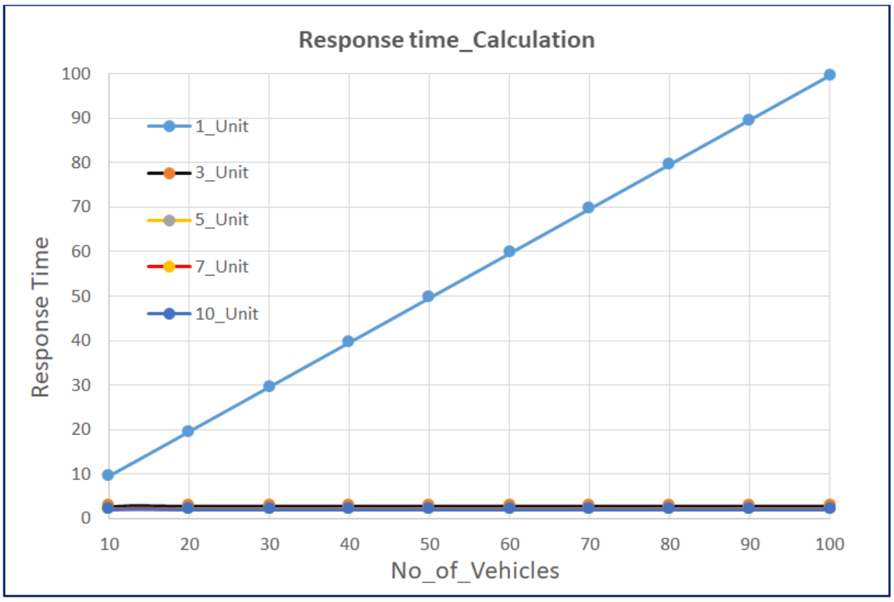

Fig.10. Response time chart for the example scenario

5. Implementation Overview

The above sections so far discuss about the theoretical construction of our system design specification of toll collection booth and later quantitative analysis of that system. While it comes to the point of implementation it needs an error free and precise way of presenting the semantic definition of our system specification. This is also applicable for the quantitative analysis of our toll collection system. To facilitate this, our system design specification and quantitative evaluation methodology have been realized by the tool supported approach. The input UML system's design specification model is generated by the graphical user interface (GUI) of Arctis tools which is incorporated with eclipse IDE. Arctis has automated model checker to verify entirely the specifications of UML models generated as a part of the system's design specification against the semantic definition of the standard UML model. Java code is generated in the background of the Arctis tool while UML diagram is generated using GUI editor of Arctis. This code is utilized to conduct the model transformation for generating the SPN model following the sematic representation SPN model for SHARPE which is responsible for conducting quantitative evaluation of the SPN model to produce numeric values. The model transformation process is driven by the transformation rules as input which is stored in library and executed by the rule engine developed in Java to produce source model into a target model [16, 17].

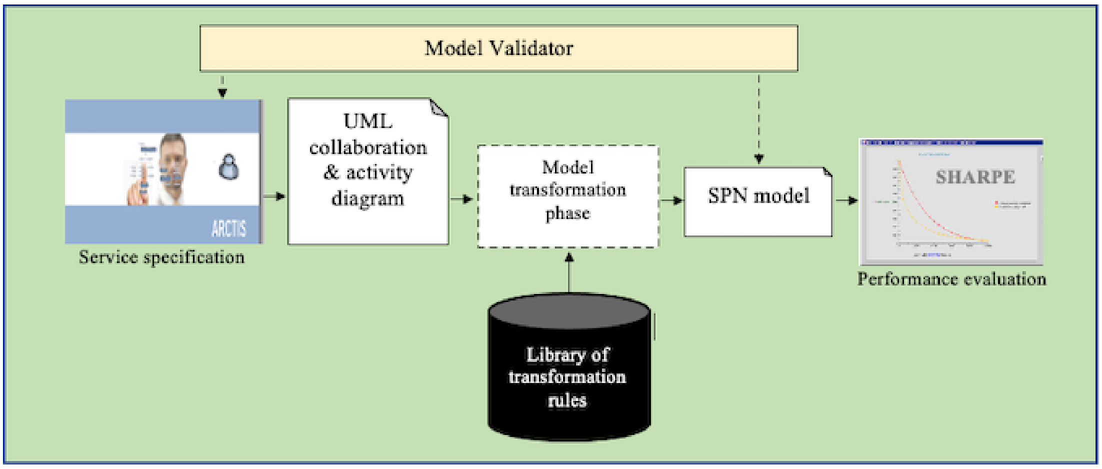

Fig.11. Tool support of our quantitative analysis

6. Conclusion

We have discussed about the quantitative study of automated vehicle toll collection system. Automated vehicle toll collection system will ease the traffic situation in Bangladesh as it will decrease the waiting time of vehicles in a budget friendly manner. As a result, traffic congestion will be reduced, and finally, this will also help improving the carbon footprint emission in Bangladesh. As traffic congestion decreases at a manageable level, work efficiency of the people of our country will also increase which will make us more productive in the long run. The main aim of our research is to carry out the quantitative analysis of the toll collection booth so that exact number of toll booths is installed that will make the process efficient in a budget friendly manner. To carry out our research, we have used UML and SPN model to capture system's dynamics correctly and provide accurate quantitative result. While implementing this research idea in real setting, if all the steps mentioned in this paper are followed flawlessly then our entire research objective will be fulfilled which assist decision maker in efficient decision-making process and it will ensure prosper of Bangladesh in the coming days.

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