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Modeling Balking And Reneging In Queues– An Approach

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Abstract

There are two approaches to modeling reneging in queuing literature viz deterministic and random. In case the patience time of customer is assumed to be random, it is the practice to further assume that customers are unaware of their state in the system so that the reneging distribution is state invariant. However, customers are often aware of their state so that it is natural to observe customers placed at a distance from the service facility to have reneging rates higher than those near the service facility. In this paper, we model such a reneging phenomenon. In addition, customers are also assumed to be of balking type with balking probabilities being a function of system state. Explicit closed form expressions of various performance measures are presented. A numerical example with design aspects has also been presented to demonstrate the results derived.

Key words: Balking, Impatience, Queuing, Reneging, Performance measure.

I. Introduction

In our modern fast-paced life, customers are hard pressed for time. Consequently waiting for service is an activity which is abhorrent. In practice, the allergy of customers to any form of waiting finds expression through balking and reneging behavior. By balking, we mean the phenomena of customers arriving at a non-empty queuing system and leaving without joining it. There is no balking from a non-empty system. Haight (1957) has provided a rationale which might influence a person to balk. It relates to the perception of the importance of being served which induces an opinion somewhere in between urgency, so that a queue of certain length will not be joined, to indifference where a non-zero queue is also joined. It is not that all customers arriving into the system balk. Some customers decide to join queue. Among those who join, it is commonly observed that some get impatient because of the act of waiting and leave the system without service. In queuing parlance, joining the system and leaving without service is known as reneging. Even though one can observe reneging and balking in our day-to-day life, it is not very often that one can locate a paper analyzing these features together in a queuing system. Even if these have been analyzed, closed form expressions of important performance measures are not available. This paper is an attempt in this direction.

We assume that balking is state dependent so that higher the queue size, higher is the probability that the customer will balk. As for modeling reneging phenomena, we assume that each customer joining the system has a Markovian patience time. Second, conventionally, it has also been assumed that customers joining the system are not aware of their position on the same so that the reneging rate is state independent. However, there are systems where the customer is aware of its state in the system. For example, customers queuing at the O.P.D. (out patient department) clinic of a hospital would know of their position in the queue. This invariably causes waiting customers to have higher rates of reneging in case their position in the queue is towards the end. It is not unreasonable then to expect that such customers who are positioned at a distance from the service facility have reneging rates, which are higher than reneging rates of customers who are near the service facility. In other words, we assume that customers are "state aware" and in this paper we model the reneging phenomenon in such a manner that the Markovian reneging rate is a function of the state of the customer in the system. Customers at higher states will be assumed to have higher reneging rates.

Reneging are of two types viz reneging till beginning of service (henceforth referred to as R_BOS) and reneging till end of service (henceforth referred to as R_EOS). In R_BOS, a customer can renege only as long as it is in the queue. It cannot renege once it begins receiving service. A common example is customers queuing at O.P.D. clinic. A customer can renege while he is waiting in queue. However once service get starts i.e. examination by medical staff begins, the customer cannot leave till it is over. On the other hand, in R_EOS, a customer can renege not only while waiting in queue but also while receiving service. Such a situation may occur in the processing or merchandising of perishable goods, hospital emergency room/O.T. handling critical patients etc. A critical patient may expire at the O.T. table of the emergency ward of a hospital; this would be an example of reneging while service is going on.

The subsequent sections of this paper are structured as follows. In section 2, we formalize the model by outlining the specifics. Section 3 contains a brief review of the literature. Section 4 and section 5 contains the derivation of steady state probabilities and performance measures. We perform sensitivity analysis in section 6. A numerical example is discussed in section 7. Concluding statements are present in section 8. The appendix contains some derivation.

II. Model description

The model we deal with in this paper is the traditional M/M/1 model with the restriction that customers may balk from a non-empty queue as well as may renege after they join the queue. We shall assume that the inter arrival and service rates are λ and μ respectively. The balking probability will be assumed to be state dependent and is taken as $(1-p^n)$, n=1,2,…

Customers joining the system are assumed to be of Markovian reneging type. We shall further assume that on joining the system the customer is aware of its state in it. Consequently, the reneging rate will be taken as a function of the customer's state in the system. As stated earlier, we assume that the patience time of such customer is random and follow Poisson law. In particular, a customer who is at state 'n' will be assumed to have random patience time following exp (ν_n). Under R_BOS, we shall assume that

$$\nu_n = \begin{cases} 0 & \text{for } n = 0,1. \\ \nu + c^{n-1} & \text{for } n = 2,3,\ldots \end{cases}$$

and under R_EOS,

$$\nu_n = \begin{cases} 0 & \text{for } n = 0. \\ \nu + c^{n-1} & \text{for } n = 1,2,3,\ldots \end{cases}$$

where c>1 is a constant.

Our aim behind this formulation is to ensure that higher the current state of a customer, higher is the reneging rate. Then it is clear that the constant c has to satisfy c>1. As for the physical implication of c, one can consider the case of c=1.2. It would imply that reneging rate would increase at a compounded rate of 20%. This reneging formulation also requires that as a customer progresses in the queue from state n ($n\geq3$) to (n-1), the reneging distribution would shift from exp ($\nu+c^{n-1}$) to ($\nu+c^{n-2}$) under R_BOS. Similarly for R_EOS. In view of the memory less property, this shifting of reneging distribution is mathematically tractable, as we shall demonstrate in the subsequent sections. To the best of our knowledge, this formulation of reneging distribution has not been attempted in literature. Advantages of the same are however obvious.

III. Literature Survey

One of the earliest works on reneging was by Barrer (1957) where he considered deterministic reneging with single server Markovian arrival and service rates. Customers were selected randomly for service. In his subsequent work, Barrer (1957) also considered deterministic reneging (of both R_BOS and R_EOS type) in a multi server scenario with FCFS discipline. The general method of solution was extended to two related queuing problems. Another early work was by Haight (1959). Ancher and Gafarian (1963) carried out an early work on Markovian reneging with Markovian arrival and service pattern. Ghosal (1963) considered a D/G/1 model with deterministic reneging. Gavish and Schweitzer (1977) also considered a deterministic reneging model with the additional assumption that arrivals can be labeled by their service requirement before joining the queue and arriving customers are admitted only if their waiting plus service time do not exceed some fixed amount. This assumption is met in communication systems. Kok and Tijms (1985) considered a single server queuing system where a customer becomes a lost customer when its service has not begun within a fixed time.

Haghighi et al. (1986) considered a Markovian multi server queuing model with balking as well as reneging. Each customer had a balking probability, which was independent of the state of the system. Reneging discipline considered by them was R_BOS. Liu et al. (1987) considered an infinite server Markovian queuing system with reneging of type R_BOS. Customers had a choice of individual service or batch service, batch service being preferred by the customer. Brandt et al. (1999) considered a S-server system with two FCFS queues, where the arrival rates at the queues and the service may depend on number of customers 'n' being in service or in the first queue, but the service rate was assumed to be constant for $n>s$. Customers in the first queue were assumed impatient customers with deterministic reneging. Boots and Tijms (1999) considered an M/M/C queue in which a customer leaves the system when its service has not begun within a fixed interval after its arrival. In this paper, they have given the probabilistic proof of 'loss probability', which was expressed in a simple formula involving the waiting time probabilities in the standard M/M/C queue.

Wang et al. (1999) considered the machine repair problem in which failed machines balk with probability (1-b) and renege according to a negative exponential distribution. Bae et al. (2001) considered an M/G/1 queue with deterministic reneging. They derived the complete formula of the limiting distribution of the virtual waiting time explicitly. Choi et al. (2001) introduced a simple approach for the analysis of the M/M/C queue with a single class of customers and constant patience time by finding simple Markov process. Applying this approach, they analyzed the M/M/1 queue with two classes of customer in which class 1 customer have impatience of constant duration and class 2 customers have no impatience and lower priority than class 1 customers. Performance measures of both M/M/C and M/M/1 queues were discussed. Zhang et al. (2005) considered an M/M/1/N framework with Markovian reneging where they derived the steady state probabilities and formulated a cost model. Some performance measures were also discussed. A numerical example was discussed to demonstrate how the various parameters of the cost model influence the optimal service rates of the system. Choudhury (2008) analyzed a single server Markovian queuing system with the added complexity of customers who are prone to giving up whenever its waiting time is larger than a random threshold-his patience time. He assumed that these individual patience times were independent and identically distributed exponential random variables. Reneging till beginning of service was considered. A detailed and lucid derivation of the distribution of virtual waiting time in the system was presented. Some performance measures were also presented. El- Paoumy (2008) also derived the analytical solution of $M^x/M/2/N$ queue for batch arrival system with Markovian reneging. In this paper, the steady state probabilities and some performance measures of effectiveness were derived in explicit forms. Another paper on Markovian reneging was by Yechiali and Altman (2008).

Xiong et al. (2008) considered a single server queue with a deterministic reneging time motivated by the timeout mechanism used in application servers in distributed computing environments. They had employed a Volterra integral equation to study the M/G/1 queue with reneging using level crossing analysis. They derived the probability generating function of number of customers present in the system and some performance measures were discussed. Jouini et al. (2009) considered two multi-class call center models with and without reneging. They assumed that customers had different priorities and the content of different types of calls was assumed as similar allowing their service times to be identical. Choudhury (2009) considered a single server finite buffer queuing system (M/M/1/K) assuming reneging customers. Both rules of reneging were considered and various performance measures presented under both rules of reneging. Xiong and Altiok (2009) studied a multi server queue with Poisson arrivals general service time distribution and deterministic reneging times. Via approximations, they provided the expression for mean waiting time. This work was motivated by the timeout mechanism used in managing application servers in transaction processing environments.

Other attempts at modeling reneging phenomenon include those by Baccelli et al (1984), Martin and Artalejo (1995), Shawky (1997), Choi, Kim and Zhu (2004), and Singh et al (2007), El- Sherbiny (2008) and El-Paoumy and Ismail (2009) etc.

An early work on balking was by Haight (1957). Another work using the concepts of balking and reneging in machine interference queue has been carried out by Al-Seedy and Al-Ibraheem (2001). Liu and Kulkarni (2008) considered an M/PH/1 queue with work load-dependent balking. They assumed that an arriving customer joined the queue and stayed until served if and only if the system workload was less than a fixed level at the time of his arrival. They also obtained the mean and LST of the busy period in the M/PH/1 queue with workload-dependent balking as a special limiting case of this fluid model. They illustrate the results with the help of numerical examples. Liu and Kulkarni (2008) also considered the virtual queuing time (vqt, also known as work-in-system, or virtual delay) process in an M/G/s queue with impatient customers. They focused on the vqt-based balking model and related it to reneging behavior of the vqt process. Jouini et al. (2008) modeled a call center as an M/M/s+M queue with endogenized customer reactions to announcements. They assumed that customers react by balking upon hearing the delay announcement and may subsequently reneged if they realized waiting time exceeds the delay that has originally announced to them. They calculated the waiting time distribution i.e. announcement coverage and subsequent performance in terms of balking and reneging. Al-Seedly et al. (2009) presented an analysis for the M/M/c queue with balking and reneging. They assumed that arriving customers balked with a fixed probability and reneged according to a negative exponential distribution. The generating function technique was used to obtain the transient solution of system those results in a simple differential equation. Yue et al. (2009) considered an M/M/2 queuing system with balking and two heterogeneous servers, server 1 and server 2. They assumed that customers arrived according to a Poisson process and form a single waiting line where two parallel servers provided heterogeneous exponential service on a first-come first-served basis. It is also assumed that server 1 is perfectly reliable and server 2 is subject to breakdowns. In this paper, they obtained the stationary condition where the system reaches a steady state and derived the steady state probabilities in a matrix form by using matrix-geometric solution method. They produced explicit expressions of some performance measures such as the mean system size, the average balking rate and the probabilities that server 2 is in various states. Numerical illustrations were also provided.

Bae and Kim (2010) considered a G/M/1 queue in which the patience time of the customers is constant. The stationary distribution of the workload of the server, or the virtual waiting time was derived by the level crossing argument. Boxma et al. (2010) considered an M/G/1 queue in which an arriving customer does not enter the system whenever its virtual waiting time i.e. the amount of work seen upon arrival, was larger than a certain random patience time. They determined the busy period distribution for various choices of the patience time distribution. Cochran et al. (2010) proposed to enable strategic decision making on future Emergency department (ED) on the basis of patient safety (rather than congestion measure). They hypothesized that the Leave without treatment (LWOT) reneging percentage is captured by the balking probability (p_k) relationship of an M/M/1/K queue. They derive the form of a binomial response nonlinear weighted regression model that best fits p_k for predicting LWOT to long term ED performance by means of Gauss- Newton linearization. Yue and Yue (2010) studied a two server Markovian network system with balking and a Bernoulli schedule under a single vacation policy where servers had different rates. After every service, only one server might take a vacation or continued to stay in the system where the vacation time followed an exponential distribution. They obtained the steady state condition, the stationary distribution of the number of customers in the system and the mean system size by using a matrix-geometric method.

Some other papers which have considered both balking and reneging are the work by Shawky and El-Paoumy (2000), El- Paoumy (2008), El- Sherbiny (2008), Shawky and El-Paoumy (2008), Pazgal et al. (2008).

IV. The System State Probabilities

In this section, the steady state probabilities are derived by the Markov process method. We first analyze the case where customers renege only from the queue Under R_BOS, let p_n denote the probability that there are 'n' customers in the system. Applying the Markov process theory, we obtain the following set of steady-state equations.

$$\lambda p_0 = \mu p_1 \tag{4.1}$$

$$\lambda p^{n-1} p_{n-1} + \{\mu + n\nu + c(c^n - 1)/(c-1)\} p_{n+1} = \lambda p^n p_n + \{\mu + (n-1)\nu + c(c^{n-1} - 1)/(c-1)\} p_n \tag{4.2}$$

:n=1,2,3,……

Solving recursively, we get (under R_BOS)

$$p_n = \left[\lambda^n p^{n(n-1)/2} \Big/ \prod_{r=1}^{n} \left\{ \mu + (r-1)\nu + c(c^{r-1}-1)/(c-1) \right\} \right] p_0 \text{; n=1,2,3,…} \quad (4.3)$$

where p_0 is obtained from the normalizing condition $\sum_{n=0}^{\infty} p_n = 1$ and is given as

$$p_0 = \left[1 + \sum_{n=1}^{\infty} \lambda^n p^{n(n-1)/2} \Big/ \prod_{r=1}^{n} \left\{ \mu + (r-1)\nu + c(c^{r-1}-1)/(c-1) \right\} \right]^{-1} \quad (4.4)$$

Under R_EOS where customer may renege from the queue as well as while receiving service, R_EOS, let q_n denote the probability that there are n customers in the system. Applying the Markov theory, we obtain the following set of steady state equations.

$$\lambda q_0 = (\mu + \nu) q_1 \quad (4.5)$$

$$\lambda p^{n-1} q_{n-1} + \left\{ \mu + (n+1)\nu + c(c^n - 1)/(c-1) \right\} q_{n+1} = \lambda p^n q_n + \left\{ \mu + n\nu + c(c^{n-1}-1)/(c-1) \right\} q_n \quad (4.6)$$

n=1,2,3,…

Solving recursively, we get (under R_EOS)

$$q_n = \left[\lambda^n p^{n(n-1)/2} \Big/ \prod_{r=1}^{n} \left\{ \mu + r\nu + c(c^{r-1}-1)/(c-1) \right\} \right] q_0 \quad ; \quad \text{n=1,2,3,…}$$

where q_0 is obtained from the normalizing condition $\sum_{n=0}^{\infty} q_n = 1$ and is given as

$$q_0 = \left[1 + \sum_{n=1}^{\infty} \lambda^n p^{n(n-1)/2} \Big/ \prod_{r=1}^{n} \left\{ \mu + r\nu + c(c^{r-1}-1)/(c-1) \right\} \right]^{-1} \quad (4.7)$$

V. Performance Measures

In general, performance measures are the specific representation of a capacity, process or outcome deemed relevant to the assessment of performance, which are quantifiable and can be documented. The main objective of any queuing study is to assess some well-defined parameters, which are designed at striking a good balance between customer satisfaction and economic considerations. In queuing theory, measures through which the nature of the quality of service can be studied are known as performance measures. Performance measures are important as issues or problems caused by queuing situations are often related to customer's dissatisfaction with service or may be the root cause of economic losses in a business. Analysis of the relevant performance measures of queuing models allows the cause of queuing issues to be identified and the impact of proposed changes to be assessed. Some of the performance measures of any queuing system that are of general interest for the evaluation of the performance of an existing queuing system and to design a new system in terms of the level of service a customer receives as well as the proper utilization of the service facilities include mean size, server utilization, customer loss and the like.

An important measure is 'L', which denotes the mean number of customers in the system. To obtain an expression for the same, we note that L=P´(1) where

$$P'(1) = \frac{d}{ds} P(s)\big|_{s=1}$$

Here P(S) is the p.g.f. of the steady state probabilities. The derivation of P´(1) is given in the appendix. Then from (A.13) we have,

$$L_{R\_BOS} = \left[\lambda p_0 / \{ p_0(p\lambda,\mu,\nu) \} - (\mu - \nu)(1-p_0) - p_0 + \left\{ c - \left(p_0 / p_0\overline{c\lambda,\mu,\nu} \right) / (c-1) \right\} \right] / \nu \text{ for } c>0, c \neq 1$$

$$L_{q(R\_BOS)} = \left[\lambda p_0 / \{ p_0(p\lambda,\mu,\nu) \} - \mu(1-p_0) - p_0 + \left\{ c - \left(p_0 / p_0\overline{c\lambda,\mu,\nu} \right) / (c-1) \right\} \right] / \nu \quad \text{for } c>0,\ c \neq 1$$

where p_0 , $p_0(c\lambda,\mu,\nu)$ and $p_0(p\lambda,\mu,\nu)$ are defined in (4.4), (A.4) and (A.5) respectively.

From (B.1) we have,

$$L_{R\_EOS} = \left[\lambda q_0 / \{ q_0(p\lambda,\mu,\nu) \} - \mu(1-q_0) - q_0 + \left\{ c - \left(q_0 / q_0\overline{c\lambda,\mu,\nu} \right) / (c-1) \right\} \right] / \nu \quad \text{for } c>0,\ c \neq 1$$

$$L_{q(R\_EOS)} = \left[\lambda q_0 / \{ q_0(p\lambda,\mu,\nu) \} - (\mu + \nu)(1-q_0) - q_0 + \left\{ c - \left(q_0 / q_0\overline{c\lambda,\mu,\nu} \right) / (c-1) \right\} \right] / \nu \text{ for } c>0, c \neq 1$$

where q_0, $q_0(c\lambda,\mu,\nu)$and $q_0(p\lambda,\mu,\nu)$ are defined in (4.7), (A.6) and (A.7) respectively.

Using Little's formula, we can calculate the average waiting time in the system and average waiting time in queue from the above mean lengths both under R_BOS and R_EOS.

Customers arrive into the system at the rate λ. However all the customers who arrive do not join the system because of balking. The effective arrival rate into the system is thus different from the overall arrival rate and is given by

$$\lambda^{e}{}_{(R\_BOS)} = \lambda p_0 + \lambda p p_1 + \lambda p^2 p_2 + \ldots.$$

$$= \lambda \sum_{n=0}^{\infty} p_n p^n \qquad (5.1)$$

$$= \lambda P(p)$$

$$= \lambda p_0 / p_0(p\lambda, \mu, \nu)$$

Similarly,

$$\lambda^{e}{}_{(R\_EOS)} = \lambda q_0 / q_0(p\lambda, \mu, \nu) \qquad (5.2)$$

We have assumed that each customer has a reneging distribution (of type R_BOS or R_EOS) following exp(ν_n). Clearly then, the reneging rate of the system would depend on the state of the system as well as reneging rule. The average reneging rate (avgrr) is given by

$$(5.3)$$

$$Avgrr_{(R\_BOS)} = \sum_{n=2}^{\infty} \{(n-1)\nu + c(c^{n-1}-1)/(c-1)\} p_n$$

$$= \nu\{P'(1) - p_1\} - \nu(1 - p_0 - p_1) + [\{P(c) - cp_1 - p_0\} - c\{1 - p_0 - p_1\}]/(c-1)$$

$$= \lambda p_0 / p_0(p\lambda, \mu, \nu) - \mu(1 - p_0)$$

$$Avgrr_{(R\_EOS)} = \sum_{n=2}^{\infty} \{n\nu + c(c^{n-1}-1)/(c-1)\} q_n$$

$$= \nu Q'(1) + [\{Q(c) - q_0 - c(1 - q_0)\}]/(c-1) \qquad (5.4)$$

$$= \lambda q_0 / q_0(p\lambda, \mu, \nu) - \mu(1 - q_0)$$

In a real life situation, customers who balk or renege represent the business lost. Management would like to know the proportion of total customers lost in order to have an idea of total business lost. Customers are lost to the system in two ways due to balking and due to reneging

Hence the mean rate at which customers are lost (under R_BOS) is

$$\lambda - \lambda^{e}{}_{(R\_BOS)} + avgrr_{(R\_BOS)} \qquad (5.5)$$

$$= \lambda - \mu(1 - p_0)$$

and the mean rate at which customers are lost (under R_EOS) is

$$\lambda - \lambda^{e}{}_{(R\_EOS)} + avgrr_{(R\_EOS)} \qquad (5.6)$$

$$= \lambda - \mu(1 - q_0)$$

These rate helps in the determination of proportion of customers lost. This proportion (under R_BOS) is given by

$$\lambda - \lambda^{e}{}_{(R\_BOS)} + avgrr_{(R\_BOS)} / \lambda \qquad (5.7)$$

$$= [\lambda - \mu(1 - p_0)] / \lambda$$

and the proportion (under R_EOS) is given by

$$\lambda - \lambda^{e}{}_{(R\_EOS)} + avgrr_{(R\_EOS)} / \lambda \qquad (5.8)$$

$$= [\lambda - \mu(1 - q_0)] / \lambda$$

Hence the proportion of customers acquiring service (under R_BOS) is

=1-proportion of customers lost

$$= (\mu/\lambda)(1 - p_0)$$

and the proportion of customers acquiring service (under R_EOS) is

=1-proportion of customers lost

$$= (\mu/\lambda)(1 - q_0)$$

The customers who leave the system do not receive service. Consequently, only those customers who reach the service station constitute the actual load of the server. From the server's point of view, this provides a measure of the amount of work he has to do. Let us call the rate at which customers reach the service station as λ^s .Then under R_BOS

$\lambda^s_{(R\_BOS)} = \lambda^e_{(R\_BOS)}$(1-proportion of customers lost due to reneging out of those joining the system)

$$= \lambda^e_{(R\_BOS)} \left\{ 1 - \sum_{n=2}^{k} (n-1)\nu p_n / \lambda^e_{(R\_BOS)} \right\}$$

$$= \lambda^e_{(R\_BOS)} - avgrr_{(R\_BOS)}$$

$$= \mu(1 - p_0)$$

In case of R_EOS, one needs to recall that customers may renege even while being served and only those customers who renege from the queue will not constitute any work for the server. Thus

$\lambda^s_{(R\_EOS)} = \lambda^e_{(R\_EOS)}$(1-proportion of customers lost due to reneging from the queue out of those joining the system)

$$= \lambda^e_{(R\_EOS)} \left\{ 1 - \sum_{n=2}^{k} (n-1)\nu q_n / \lambda^e_{(R\_EOS)} \right\}$$

$$= \lambda^e_{(R\_EOS)} - avgrr_{(R\_EOS)}$$

$$= \mu(1 - q_0)$$

In order to ensure that the system is in steady state, it is necessary for the rate of customers reaching the service station to be less than the system capacity. This translates to

$$(\lambda^s / \mu) < 1$$

IV. Sensitivity Analysis

We have assumed that there are essentially three parameters viz: λ, μ and ν relating to the stochastic nature of arrival, service and reneging patterns. Various reasons may influence these parameters so that on different occasions these may undergo change. From managerial point of view, an idle server is a waste. Similarly for low server utilization. It is therefore interesting to examine and understand how server utilization varies in response to change in system parameters. We place below the effect of change in these system parameters on server utilization. For this purpose, we shall follow the following notational convention in the rest of this section.

p_n (λ, μ, ν) and q_n (λ, μ, ν)will denote the probability that there are 'n' customers in a system with parameters λ, μ, ν in steady state under R_BOS and R_EOS respectively.

i) Let $\lambda_1 > \lambda_0$. Then

$$\frac{p_0(\lambda_1, \mu, \nu)}{p_0(\lambda_0, \mu, \nu)} < 1$$

$$\Rightarrow \frac{(\lambda_0 - \lambda_1)}{\mu} + \frac{p(\lambda_0^2 - \lambda_1^2)}{\mu(\mu + \nu + c)} + \ldots\ldots < 0$$

which is true and hence $p_0 \downarrow as\ \lambda \uparrow$.

ii) Let $\mu_1 > \mu_0$. Then

$$\frac{p_0(\lambda, \mu_1, \nu)}{p_0(\lambda, \mu_0, \nu)} > 1$$

$$\Rightarrow \lambda\left(\frac{1}{\mu_0} - \frac{1}{\mu_1}\right) + \lambda^2 p \left\{ \frac{1}{\mu_0(\mu_0 + \nu + c)} - \frac{1}{\mu_1(\mu_1 + \nu + c)} \right\} + \ldots\ldots > 0$$

which is true and hence $p_0 \uparrow \quad as\ \mu \uparrow$.

iii) Let $\nu_1 > \nu_0$. Then

$$\frac{p_0(\lambda,\mu\ ,\nu_1,k)}{\mathrm{p}_0(\lambda,\mu,\nu_0,k)}>1$$

$$=\lambda\left(\frac{1}{\mu}-\frac{1}{\mu}\right)+\lambda^2 p\left\{\frac{1}{\mu(\mu+\nu_0+c)}-\frac{1}{\mu(\mu+\nu_1+c)}\right\}+\ldots\ldots.>0$$

which is true and hence $p_0 \uparrow as\ \nu \uparrow$.

The following can similarly be shown.

iv) $q_0 \downarrow as\ \lambda \uparrow$

v) $q_0 \uparrow as\ \mu \uparrow$

vi) $q_0 \uparrow as\ \nu \uparrow$

These results state that an increase in arrival rate would result in lowering of the fraction of time the server is idle. An increase in service rate would mean the server is able to work efficiently so that it can process same amount of work quickly. This translates to higher server idle time. An increase in reneging rate would mean the server has fewer work to do and hence higher fraction of idle time.

VII. Numerical example.

To illustrate the use of our results, we consider the following example from Ravindran, Phillips and Solberg (1987, page 338). It concerns a grain elevator at a small town in one of the plains states where wheat is the principal crop. During the harvest season, trucks loaded with wheat from the fields arrive at the elevator, where they must quickly deposit their load and return to fields for another. The check in process involves weighing the truck, drawing samples for moisture and contamination tests, and a few other details before the load can be dumped through a grate.

The farmers are very concerned about getting their crop off the field and into the elevator quickly. Once the wheat is ripe, it is highly vulnerable to rain or wind. Any delay could threaten a significant portion of a farmer's income for the whole year. Of course, all of the fields in a region ripen about the same time, so it is not surprising that a traffic problem could develop at the elevator. The average interarrival time is estimated to be 9/hr, further 10 trucks are serviced on the average.

Given the nature of the problem, it is natural that there will be balking as well as reneging. The primary concern of the farmers is to ensure that the crop does not get destroyed. Consequently, the bigger the queue, the more impatient the farmer would be. Our model assumptions can model such a scenario. We shall assume that reneging distribution is state dependent following exp(ν_n) where ν_n is as described in section 2. Specifically, we shall assume ν=2/hr and consider two scenarios with c viz c=1.1 and c=1.2. Here c=1.1 would imply that reneging rate would increase at a compounded rate of 10% state wise whereas c=1.2 would imply a compounded rate of 20%. At the same time because of farmers concern, some of them will balk. We are assuming a state dependent balking probability of (1-p^n), n=1,2,…with p=0.98. This will imply that in case there is one customer in the system, an arriving customer will balk with probability 0.02 and in case there are two in system, the arriving customer will balk with probability 0.0396. With these parameters, various performance measures of interest have been computed using a FORTRAN 77 program coded by the authors. The results are presented in the following table:

Table 1: Table of Performance Measures (assuming λ=9/hr, μ=10/hr, ν=2/hr and p=0.98.)

Performance Measure	c=1.1	c=1.2
Average length of system	1.31965	1.29191
Average length of queue	0.64908	0.62482
Mean reneging rate	2.06054	2.10017
Average balking rate	0.23374	0.22896
Proportion of customer lost due to balking and reneging	0.25492	0.25879
Mean rate of customers lost	2.29428	2.32913
Proportion of customer acquiring service	0.74508	0.74121
Effective arrival rate in to the system	8.76626	8.77104
Arrival rate of customer reaching service station	6.70572	6.67087
Fraction of time server is idle	0.32943	0.33291

From the above table it is clear that as the compounded rate of reneging increases from 10% to 20%, average length of system, average length of queue, proportion of customers acquiring service and arrival rate of customer reaching service station decreases. It is also seen that the effective arrival rate, proportion of customer lost due to reneging and balking and fraction of time server is idle increases with the increase in the compounded rate. These results are expected. The elevators management may look into the fact that at least one in four customers are lost due to balking and reneging. This is an area of concern for them.

VIII. Conclusion.

The modeling of queuing system with balking and reneging presents a challenge. Here we have assumed that balking probabilities and reneging rates are state dependent. To the best of our knowledge, this has not been attempted. We have presented explicit closed form expression of a number of performance measures. The emphasis has been on understanding the extent of customer's loss. We belief these measures can assist system manager to reduce business loss. The limitations of this work stem from the Markovian assumptions. Extension of our results for general distribution is a pointer to future research.

Appendix A. Derivation of P´(1) under R_BOS:

Let P(s) denote the probability generating function, which is given by $P(s)=\sum_{n=0}^{\infty} p_n s^n$

From equation (4.2) we have

$\lambda p^{n-1} p_{n-1} + \{\mu + n\nu + c(c^n -1)/(c-1)\} p_{n+1} = \lambda p^n p_n + \{\mu + (n-1)\nu + c(c^{n-1}-1)/(c-1)\} p_n$; n=1,2,…

Now multiplying both sides of the equation by s^n and summing over n

$$\Rightarrow \lambda s\sum_{n=1}^{\infty} p^{n-1}p_{n-1}s^{n-1} - \lambda\sum_{n=1}^{\infty} p^n p_n s^n = \sum_{n=1}^{\infty} \{\mu+(n-1)\nu + c(c^{n-1}-1)/(c-1)\} p_n s^n - -\frac{1}{s}\sum_{n=1}^{\infty}\{\mu+n\nu+c(c^{n-1}-1)/(c-1)\}p_{n+1}s^{n+1}$$

$$\Rightarrow \lambda sP(ps) - \lambda\{P(ps)-p_0\} = \mu\{P(s)-p_0\} + \nu s\{P'(s)-p_1\} - \nu\{P(s)-p_0-p_1 s\} + \sum_{n=1}^{\infty}\{(c^n-c)/(c-1)\}p_n s^n$$

$$-1/s\left[\mu\{P(s)-p_0-p_1s\} + \nu s\{P'(s)-p_1\} - \nu\{P(s)-p_0-p_1s\} + \sum_{n=2}^{\infty}\{(c^{n+1}-c)/(c-1)\}p_{n+1}s^{n+1}\right]$$

$$\Rightarrow \lambda sP(ps)-\lambda\{P(ps)-p_0\} = \mu\{P(s)-p_0\}+\nu s\{P'(s)-p_1\}-\nu\{P(s)-p_0-p_1s\}+\{1/(c-1)\}\{cp_1s^1+c^2p_2s^2+\ldots\}$$

$$\{c/(c-1)\}\{p_1s^1+p_2s^2+\ldots\} - 1/s\left[\begin{array}{l}\mu\{P(s)-p_0-p_1s\}+\nu s\{P'(s)-p_1\}-\nu\{P(s)-p_0-p_1s\}+\{1/(c-1)\}\{c^2p_2s^2+c^3p_3s^3\ldots\}\\ -\{c/(c-1)\}\{p_2s^2+p_3s^3+\ldots\}\end{array}\right]$$

$$\Rightarrow \lambda sP(ps)-\lambda\{P(ps)-p_0\}=\mu\{P(s)-p_0\}+\nu s\{P'(s)-p_1\}-\nu\{P(s)-p_0-sp_1\}$$

$$+\{1/(c-1)\}\{P(cs)-p_0-p_1cs-cP(s)+cp_0+cp_1s\}-\mu/s\{P(s)-p_0-p_1s\}-\nu\{P'(s)-p_1\}+(\nu/s)\{P(s)-p_0-p_1s\}$$

$$+1/(c-1)s\{P(cs)-p_0-p_1cs-cP(s)+cp_0+cp_1s\}$$

$$\Rightarrow \lambda sP(ps)-\lambda P(ps)+\lambda p_0 = \mu P(s)-\mu p_0+\nu sP'(s)-\nu P(s)+\nu p_0+P(cs)/(c-1)-p_0/(c-1)-cP(s)/(c-1)+$$

$$cp_0/(c-1)-\mu P(s)/s+(\mu p_0)/s+\mu p_1-\nu P'(s)+\nu p_1+\nu/s\,P(s)-(\nu p_0)/s-\nu p_1-P(cs)/\{(c-1)s\}+cP(s)/\{(c-1)s\}-p_0/s$$

$$\Rightarrow \nu P'(s)-\nu sP'(s)=\mu P(s)-\mu p_0-\lambda sP(ps)+\lambda P(ps)-\lambda p_0$$

$$-\nu P(s)+\nu p_0-p_0/(c-1)+P(cs)/(c-1)-\{cP(s)\}/(c-1)+(cp_0)/(c-1)-\{\mu P(s)\}/s$$

$$+\{\mu p_0\}/s+\{(\mu\lambda)p_0\}/\mu+(\nu/s)P(s)-(\nu p_0)/s-P(cs)/\{(c-1)s\}+\{cP(s)\}/\{(c-1)s\}-p_0/s$$

$$\Rightarrow \nu(1-s)P'(s)=[\nu/s-\mu/s+\{c/(c-1)s\}](1-s)P(s)+\{\mu p_0(1-s)\}/s+\{p_0(1-s)\}/s$$

$$-\{\nu p_0(1-s)\}/s-\{P(cs)(1-s)\}/\{s(c-1)\}-p_0(1-s)/s+\lambda P(ps)(1-s)$$

$$\Rightarrow \nu P'(s)=\{\nu/s-\mu/s+c/(c-1)\}P(s)+(\mu p_0)/s-(\nu p_0)/s-P(cs)/\{s(c-1)\}-p_0/s+\lambda P(ps)$$

$$\Rightarrow P'(s)=(1/\nu)\{\nu/s-\mu/s+c/(c-1)\}P(s)+(\mu p_0)/s-(\nu p_0)/s-P(cs)/\{s(c-1)\}-p_0/s+\lambda P(ps)$$

Now

$$\lim_{s\to 1-} p'(s) = \lim_{s\to 1-} (1/\nu)\left[\{\nu/s-\mu/s+c/(c-1)\}P(s)+(\mu p_0)/s-(\nu p_0)/s-P(cs)/\{s(c-1)\}-p_0/s+\lambda P(ps)\right]$$

$$\Rightarrow p'(1) = (1/\nu)\left[\{\nu-\mu+c/(c-1)\}+\mu p_0-\nu p_0-P(c)/(c-1)-p_0+P(p)\right]$$

$$=(1/\nu)\left[P(p)-(\mu-\nu)(1-p_0)-p_0+\{c-P(c)/(c-1)\}\right] \qquad (A.1)$$

Here $P(c)=\sum_{n=0}^{\infty} p_n(\lambda,\mu,\nu)c^n$ where the symbol $p_n(\lambda,\mu,\nu)$ is as described in section 6. We use p_n and $p_n(\lambda,\mu,\nu)$ interchangeably. However should any of the parameters λ,μ,ν change, it is explicitly stated. To obtain a closed form expression for P(c) and P(p), let us for the time being, consider two another queuing systems with parameters and assumptions similar to the queuing system we are presently considering except that the arrival rate is 'cλ' and 'pλ' respectively. For these new systems, the steady state equations are same as (4.1), (4.2) and (4.3) with 'λ' replaced by 'cλ' and 'pλ' respectively. Denoting the steady state probabilities of these new systems by $p_n(c\lambda,\mu,\nu)$ and $p_n(p\lambda,\mu,\nu)$ respectively, we can obtain under R_BOS

$$p_n(c\lambda,\mu,\nu)=\left[(c\lambda)^n p^{n(n-1)/2}\Big/\prod_{r=1}^{n}\{\mu+(r-1)\nu+c(c^{r-1}-1)/(c-1)\}\right]p_0(c\lambda,\mu,\nu) \quad n=1,2,\ldots \qquad (A.2)$$

$$p_n(p\lambda,\mu,\nu)=\left[(p\lambda)^n p^{n(n-1)/2}\Big/\prod_{r=1}^{n}\{\mu+(r-1)\nu+c(c^{r-1}-1)/(c-1)\}\right]p_0(p\lambda,\mu,\nu) \quad n=1,2,\ldots \qquad (A.3)$$

where

$$p_0(c\lambda,\mu,\nu)=\left[1+\sum_{n=1}^{\infty}(c\lambda)^n p^{n(n-1)/2}\Big/\prod_{r=1}^{n}\{\mu+(r-1)\nu+c(c^{r-1}-1)/(c-1)\}\right]^{-1} \qquad (A.4)$$

$$p_0(p\lambda,\mu,\nu)=\left[1+\sum_{n=1}^{\infty}(p\lambda)^n p^{n(n-1)/2}\Big/\prod_{r=1}^{n}\{\mu+(r-1)\nu+c(c^{r-1}-1)/(c-1)\}\right]^{-1} \qquad (A.5)$$

and under R_EOS,

$$q_n(c\lambda,\mu,\nu)=\left[(c\lambda)^n p^{n(n-1)/2}\Big/\prod_{r=1}^{n}\{\mu+r\nu+c(c^{r-1}-1)/(c-1)\}\right]q_0(c\lambda,\mu,\nu) \quad n=1,2\ldots.$$

$$q_n(p\lambda,\mu,\nu)=\left[(p\lambda)^n p^{n(n-1)/2}\Big/\prod_{r=1}^{n}\{\mu+r\nu+c(c^{r-1}-1)/(c-1)\}\right]q_0(p\lambda,\mu,\nu) \quad n=1,2\ldots.$$

where

$$q_0(c\lambda,\mu,\nu)=\left[1+\sum_{n=1}^{\infty}(c\lambda)^n p^{n(n-1)/2}\Big/\prod_{r=1}^{n}\{\mu+r\nu+c(c^{r-1}-1)/(c-1)\}\right]^{-1} \qquad (A.6)$$

$$q_0(p\lambda,\mu,\nu)=\left[1+\sum_{n=1}^{\infty}(p\lambda)^n p^{n(n-1)/2}\Big/\prod_{r=1}^{n}\{\mu+r\nu+c(c^{r-1}-1)/(c-1)\}\right]^{-1} \qquad (A.7)$$

Let $P(S;c\lambda,\mu,\nu)$ denotes the probability generating function of the steady state probabilities of this new queuing system so that

$$P(S;c\lambda,\mu,\nu)=\sum_{n=0}^{\infty}p_n(c\lambda,\mu,\nu)s^n$$

$$P(c)=\sum_{n=0}^{\infty}p_n(\lambda,\mu,\nu)c^n$$

Now,
$$=p_0+\sum_{n=1}^{\infty}\left[(c\lambda)^n p^{n(n-1)/2}\Big/\prod_{r=1}^{n}\{\mu+(r-1)\nu+c(c^{r-1}-1)/(c-1)\}\right]p_0$$

$$\Rightarrow[(P(c)-p_0)/p_0]=\sum_{n=1}^{\infty}\left[(c\lambda)^n p^{n(n-1)/2}\Big/\prod_{r=1}^{n}\{\mu+(r-1)\nu+c(c^{r-1}-1)/(c-1)\}\right] \quad (A.8)$$

Now, putting S=1 in $P(S;c\lambda,\mu,\nu)$ we get

$$P(1;c\lambda,\mu,\nu)=p_0(c\lambda,\mu,\nu)+\sum_{n=1}^{\infty}p_n(c\lambda,\mu,\nu)$$

$$\Rightarrow 1=p_0(c\lambda,\mu,\nu)+\sum_{n=1}^{\infty}\left[(c\lambda)^n p^{n(n-1)/2}\Big/\prod_{r=1}^{n}\{\mu+(r-1)\nu+c(c^{r-1}-1)/(c-1)\}\right]p_0(c\lambda,\mu,\nu) \quad \text{using (A.2)}$$

$$\Rightarrow 1=p_0(c\lambda,\mu,\nu)+\{(P(c)-p_0)/p_0\}p_0(c\lambda,\mu,\nu) \quad \text{using (A.8)}$$

$$\Rightarrow P(c)=p_0/p_0(c\lambda,\mu,\nu) \quad (A.9)$$

Similarly under R_EOS, $Q(c)=q_0/q_0(c\lambda,\mu,\nu)$ (A.10)

Proceeding in the similar way, we can obtain under R_EOS,

$$P(p)=p_0/p_0(p\lambda,\mu,\nu) \quad (A.11)$$

and under R_EOS it is given by

$$Q(p)=q_0/q_0(p\lambda,\mu,\nu) \quad (A.12)$$

Using these in (9.1.1) we obtain (for c>1)

$$P'(1)=(1/\nu)\left[(\lambda p_0)/p_0(p\lambda,\mu,\nu)-(\mu-\nu)(1-p_0)-p_0+\{c-(p_0/p_0\overline{c\lambda,\mu,\nu})\}/(c-1)\right] \quad (A.13)$$

Appendix B. Derivation of Q´(1) under R_EOS:

From equation (4.6) we have,

$$\lambda p^{n-1}q_{n-1}+\{\mu+(n+1)\nu+c(c^n-1)/(c-1)\}q_{n+1}=\lambda p^n q_n+\{\mu+n\nu+c(c^{n-1}-1)/(c-1)\}q_n \quad n=1,2,..$$

Multiplying both sides of this equation by s^n and summing over n from we get

$$\lambda s\sum_{n=1}^{\infty}p^{n-1}q_{n-1}s^{n-1}-\lambda\sum_{n=1}^{\infty}p^n q_n s^n=\sum_{n=1}^{\infty}\{\mu+n\nu+c(c^{n-1}-1)/(c-1)\}p_n s^n-\frac{1}{s}\sum_{n=1}^{\infty}\{\mu+(n+1)\nu+(c(c^n-1)/(c-1))\}p_{n+1}s^{n+1}$$

Proceeding in a manner similar to section (9.1), we obtain,

$$Q'(1)=\left[\lambda q_0/\{q_0(p\lambda,\mu,\nu)\}-\mu(1-q_0)-q_0+\{c-(q_0/q_0\overline{c\lambda,\mu,\nu})/(c-1)\}\right]/\nu \quad (B.1)$$

using (A.10) and (A.12)

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