Research of automated checkpoint systems in visitors free passage mode

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***Abstract*— This paper discusses features of automated checkpoint systems (ACS) turnstiles dynamics in public venues and mass gathering events. Turnstiles are servers from the point of view of queuing systems theory. Stages of visitors exit from the facility at the end of the event are studied. The server mathematical model and the flow of clients arriving at the input of a server are described. Estimates of the maximum queue length and the maximum waiting duration for leaving the mass gathering events venues for two different policies of visitor behavior have been obtained. Scientifically proven recommendations for the behavior of visitors when leaving the facilities of public events are given.**

***Keywords*— automated checkpoint systems, multichannel nonstationary queue system, simulation**

I. Introduction

Participation in mass gatherings is an integral part of the life of every modern person. People are in queues at subway, airports, railway stations, when attending concerts or participating in meetings and processions. At the same time, mass gatherings of people pose a danger both from the point of view of the epidemiological situation and from the point of view of a scrum. One of the first measures to counter the spread of COVID-19 infection was the ban on mass events.

Visitors safety during mass events could be separated to stages. The following stages can be distinguished:

1) the stage of visitors arriving at public venue holding of a mass event;
2) the stage of act event;
3) the stage of visitors exits.

It is possible to improve the quality of service for visitors and reduce the risks of emergencies using automated checkpoint systems (ACS). It is a best practice for mass gathering event. Turnstiles in ACS are used as a separate server, which provide automatic ticket check. ACS can made decisions on admission or refusal to pass concrete visitor and collect of statistics.

It is necessary to use estimates of quantitative characteristics of visitor flows for a design of safety measures. These measures should ensure safety of participants in a mass gathering event at each stage. Such quantitative characteristics can be: the maximum length of the queue to the turnstiles, the maximum waiting duration, etc.). Those characteristics can be obtained using the corresponding simulations of individual turnstiles and ACS in general.

Single turnstile in ACS at stage 1 and stage 3, highlighted above, is a single-channel non-stationary queuing system (NQS) from the point of view of queuing system theory (QS). Whole ACS respectively is a multichannel NQS, at the input of which a flow of clients for service with a time-varying rate arrives. NQS models are also good representation of various technical systems [1, 2], including: Internet banks, at the time of mass payments, equipment of mobile operators, passenger control devices at airports and train stations, etc.

The features of the functioning of the ACS at stage 1 were studied earlier in [3-5]. In these works:

1. it is proven that the service rate the visitors of mass events with a single turnstile is a random value with a triangular distribution law. This distribution law set by the minimum service time, maximum service time, the most probable service time [4];

$$p\{\xi\} = \begin{cases} 0, \text{ if } \xi < 1, \\ \dfrac{2M[\xi]}{9(M[\xi]-1)}(\xi-1), \text{ if } 1 \le \xi < M[\xi], \\ \dfrac{2M[\xi]}{9(M[\xi]-10)}(\xi-10), \text{ if } M[\xi]<\xi \le 10, \\ 0, \text{ if } \xi > 10, \end{cases} \quad (1)$$

2. Choice of input rate law of visitor flow is justified according to football match visitors flow:

$$\lambda(t) = \begin{cases} \lambda_1(t), T_1 \le t \le T_2, \\ \lambda_2(t), T_2 \le t \le T_3, \end{cases} \quad (2)$$

$\lambda_1(t)$ is monotonically increasing function $\lambda_1(T_1) = 0$, $\lambda_1(T_2) = \lambda_{\max}$, $\lambda_2(t)$ is monotonically decreasing function, $\lambda_2(T_2) = \lambda_{\max}$, $\lambda_2(T_3) = 0$ [4];

3. An algorithm for the simulation of the ACS based on the use of piecewise constant approximation of the function $\lambda = \lambda(t)$:

$$\lambda(t) = \sum_{k=0}^{K} \left(\theta(t_k - t) - \theta(t_{k+1} - t)\right) \cdot \overline{\lambda}_k, \quad (3)$$

where

$\theta(t-\xi)$ is the step function

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$$\theta(t-\xi)=\begin{cases}0, t<\xi,\\1, t\geq\xi,\end{cases} \qquad (4)$$

$\overline{\lambda}_k$ is average value of function $\lambda_{\exp}(t)$ on interval $[t_k, t_{k+1}]$ [3]. Also, program realization of this algorithm proposed.

4. The choice of the step of the piecewise constant approximation of the function $\lambda=\lambda(t)$ is proven [5];

5. It has been proved that the dynamics of the NSQ, at the input of which the flow of clients arrives with the rate $\lambda=\lambda(t)$ specified by (2), can be described by a finite set of macroscopic characteristics that do not depend on time, but depend on T_1, T_2, T_3, $\lambda_{\max}$ [5].

Stage number 3 is also important to ensure the safety of visitors to public events. It differs from stage 1 by a significantly greater value $\lambda_{\max}$ and a smaller duration interval $[T_1, T_3]$.

Indeed, it may occur that all visitors of a mass gathering event are simultaneously in line at the corresponding turnstile at the end of the event. However, the authors failed to find earlier studies of the features of the NQS dynamics in the mode under discussion. That is why chosen research topic relevant.

The article discusses the results of simulation of the ACS, at stage 3 of a mass event.

II. Input Rate Model and Service Rate Model

Analysis of the video recordings of the visitors exit process from football matches shows that after the final whistle they are sent to the turnstiles of the access control system, operating in free exit mode. For a certain interval of time $[T_1;T_2]$, the input rate of clients increases from 0 to a some maximum value $\lambda_{\max}$. Further, during another time interval $[T_2;T_3]$, the input rate of clients decreases from $\lambda_{\max}$ to zero. For approximation $\lambda=\lambda(t)$ a separate linear approximation was applied on time intervals $[T_1;T_2]$ and $[T_2;T_3]$ taking into account the above studies.

The service rate of the exit through the turnstiles was studied in a similar way. Estimation of the duration of passage of one visitor through the turnstile ξ, showed that this characteristic of the NQS server is a random variable varying in the range of 1 to 10 s. Whose distribution density is described by a triangular distribution law such that the expected value of ξ = 1 s. The corresponding service rate of clients is μ = 60 clients per minute.

III. Methodology

Experiment 1. The goal of the experiment is to study the influence of the input rate value of T_2 on the macroscopic characteristics under condition that $T_3 - T_1$= const. It was assumed that:

- input rate in the is described by functions which are shown in Figure 1;
- the moment of the end of the event T_1 = 0 min., starting from which the first orders appear;
- the expected number of clients is S_0 = 25000;
- the number of experiments R = 20;
- the number of servers in ACS m = 15.

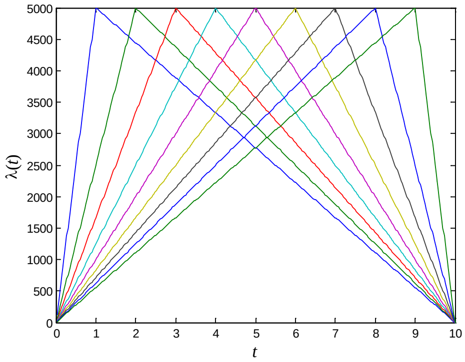

Fig. 1. Dependences of input rate in the multichannel NQS studied (experiment 1)

Experiment 2. The goal of the experiment is to study the influence of the input rate value of T_3 on the macroscopic characteristics under condition that $T_2=5$, $T_3>10$ и $T_3-T_2\neq const$. It was assumed that:

- input rate in the is described by functions which are shown in Figure 2;
- the moment of the end of the event T_1 = 0 min., starting from which the first orders appear;
- the expected number of clients is S_0 = 25000;
- the number of experiments R = 20;
- the number of servers in ACS m = 15.

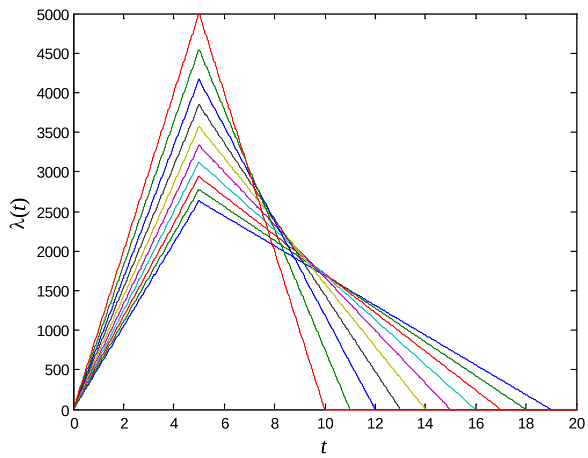

Fig. 2. Dependences of input rate in the multichannel NQS studied (experiment 2)

IV. Results

The dependences of the macroscopic quantitative characteristics of NQS on the parameters T_2, T_3 of the input rate $\lambda=\lambda(t)$ were calculated as a result of experiments:

- maximum queue length $L_{\max}$;
- maximum waiting duration in a queue $\tau^w_{\max}$;
- time for service 97% of visitors of a mass gathering event T_{All}.

Typical dependences of the maximum queue length on parameters on parameters T_2, T_3 (experiment 1 and 2 respectively) are shown in Figure 3 and Figure 4.

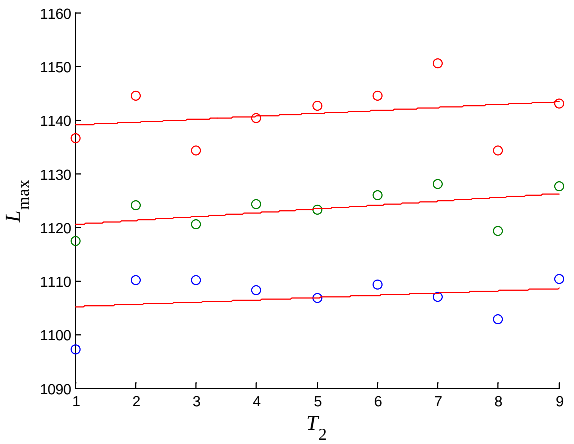

Fig.3. Dependency $L_{\max}(T_2)$ and its the upper $L_{\max}^{<up>} = L_{\max}^{<up>}(T_2)$ and lower $L_{\max}^{<low>} = L_{\max}^{<low>}(T_2)$ boundaries of the range of possible values $L_{\max}$ (experiment 1)

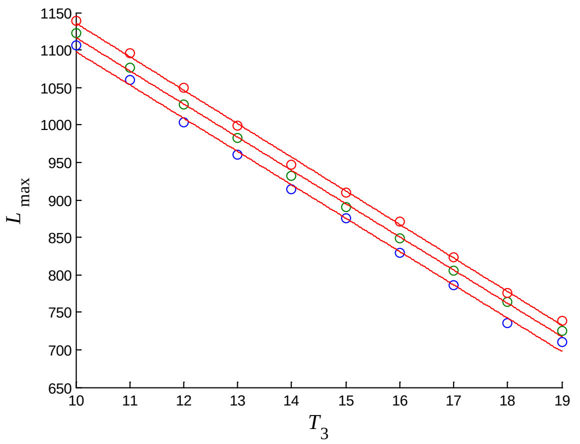

Fig.4. Dependency $L_{\max}(T_3)$ and its $L_{\max}^{<up>} = L_{\max}^{<up>}(T_3)$ upper and $L_{\max}^{<low>} = L_{\max}^{<low>}(T_3)$ lower boundaries of the range of possible values $L_{\max}$ (experiment 2)

Figure 3 shows that for experiment 1 the dependence $L_{\max} = L_{\max}(T_2)$ of the maximum queue length $L_{\max}$ from T_2, which can be approximated by the function $L_{\max}(T_2) = 0.54 \cdot T_2 + 1138$. This dependency turns out to be practically independent from T_2. Indeed, when changing T_2 from 1 to 9, the value $L_{\max}$ changes from 1117 to 1127, i.e. no more than 0.9%. This result is explained by the fact that the dependences $\lambda_k = \lambda_k(t)$ $k = \overline{1,9}$ are such that for all k $\max(\lambda_k) = const$.

Figure 4 shows that in experiment 2 the maximum queue length $L_{\max}$ turns out to be a linear function $L_{\max}(T_3) = -44.8 \cdot T_2 + 1584$ from T_3. The value of this function, when T_3 changing from 10 to 19, this value changes from 1122 to 724, i.e. more than 35%. This result is explained by the fact that the dependences $\lambda_k = \lambda_k(t)$, $k = \overline{1,9}$ are such that an increase of T_3 proportionally decreases the maximum value $\lambda_{\max}$ of input rate (see Fig. 2).

Typical dependencies of queue length to a single server (gate) on time are shown on Fig. 5 and Fig. 6.

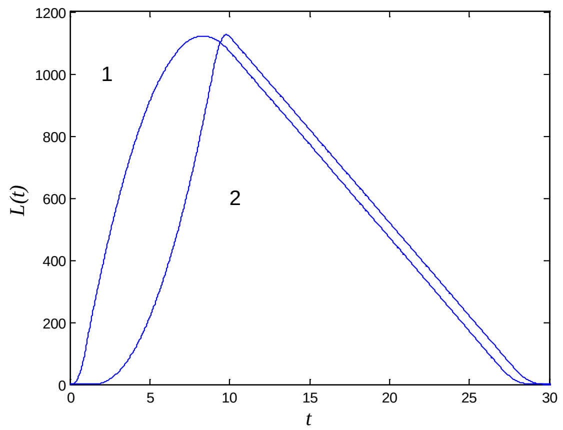

Fig.5. Typical dependency $L = L(t)$: $1 - T_2 = 1$; $2 - T_2 = 9$ (experiment 1)

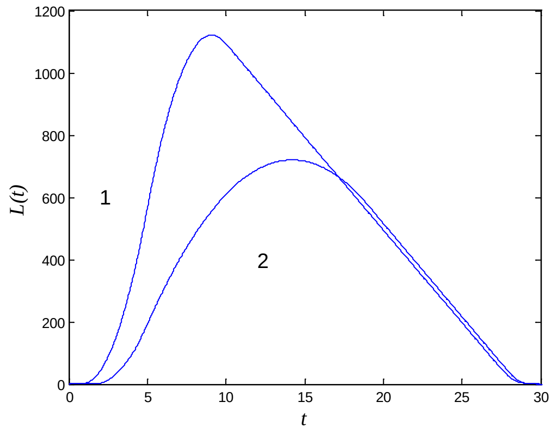

Fig.6. Typical dependency $L = L(t)$: $1 - T_3 = 10$; $2 - T_3 = 19$ (experiment 2)

Figure 5 and Figure 6 shows that indeed the functions $L = L(t)$, regardless of the input rate parameters T_2, T_3 on the considered time interval, first monotonically increase from 0 to $L_{\max} = \max(L(t))$ and then, after reaching the maximum values at the time $t_{L_{\max}} = \arg\max(L(t))$, they monotonically decrease. In the first experiment, the value $L_{\max}$ practically does not change with an increase of a value T_2, while in the second experiment, the value $L_{\max}$ decreases with an increase T_3 (and proportional decrease $\lambda_{\max}$, experiment 2). The dependence of the maximum waiting duration $\tau_{\max}^{w}$ for different parameters of the input intensity is shown in Figure 7 and Figure 8.

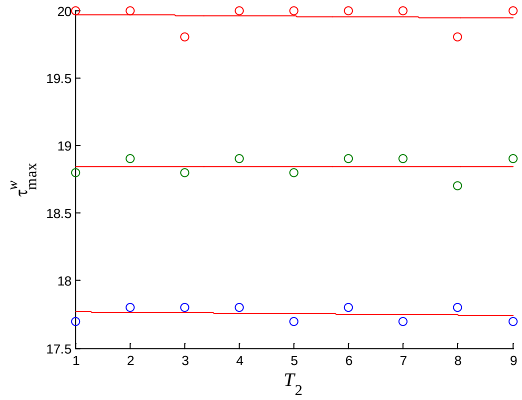

Fig.7. Dependency $\tau^w_{\max} = \tau^w_{\max}(T_2)$, its the upper $\left[\tau^w_{\max}\right]^{\langle up\rangle} = \left[\tau^w_{\max}\right]^{\langle up\rangle}(T_2)$ and lower $\left[\tau^w_{\max}\right]^{\langle low\rangle} = \left[\tau^w_{\max}\right]^{\langle low\rangle}(T_2)$ $L^{<low>}_{\max} = L^{<low>}_{\max}(T_2)$ boundaries of the range of possible values $\tau^w_{\max}$ (experiment 1)

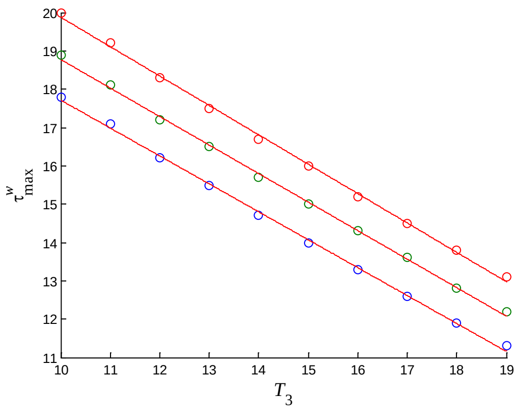

Fig.8. Dependency $\tau^w_{\max} = \tau^w_{\max}(T_3)$, and its the upper $\left[\tau^w_{\max}\right]^{\langle up\rangle} = \left[\tau^w_{\max}\right]^{\langle up\rangle}(T_3)$ lower $\left[\tau^w_{\max}\right]^{\langle low\rangle} = \left[\tau^w_{\max}\right]^{\langle low\rangle}(T_3)$ boundaries of the range of possible values $\tau^w_{\max}$ (experiment 2)

Figure 7 shows that the dependence $\tau^w_{\max} = \tau^w_{\max}(T_2)$ for experiment 1 can be approximated by a linear function $f(T_2) = -0.003 \cdot T_2 + 19.97$. Its values practically do not depend on T_2, since when changing T_2 from 1 to 9, this value changes from 18.8 to 18.9, i.e. no more than 0.5%. Figure 8 shows that the dependence $\tau^w_{\max} = \tau^w_{\max}(T_3)$ for experiment 2 can be approximated by a linear function $\tau^w_{\max}(T_3) = -0.76 \cdot T_3 + 27.55$ When changing T_3 from 10 to 19, this value changes from 18.9 to 12.2, i.e. on 54%.

Dependence of the moment at which 97% of clients were served, from various parameters of the input rate are sown in Figure 9 and Figure 10.

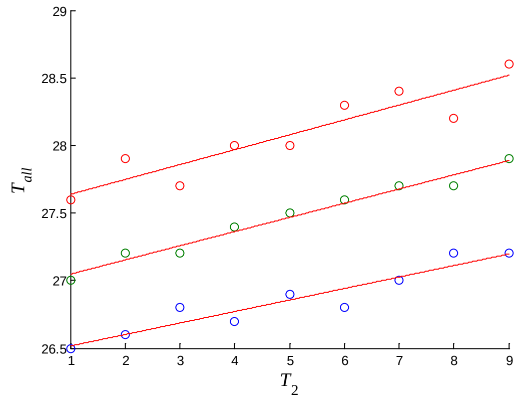

Fig.9 Dependency $T_{All} = T_{All}(T_2)$, its upper $T^{\langle up\rangle}_{All} = T^{\langle up\rangle}_{All}(T_2)$ and lower $T^{\langle low\rangle}_{All} = T^{\langle low\rangle}_{All}(T_2)$ boundaries of the range of possible values T_{All} (experiment 1);

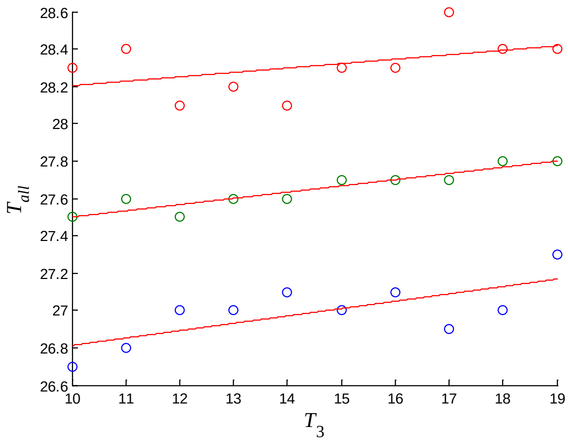

Fig.10 Dependency $T_{All} = T_{All}(T_3)$, its upper $T^{\langle up\rangle}_{All} = T^{\langle up\rangle}_{All}(T_3)$ and lower $T^{\langle low\rangle}_{All} = T^{\langle low\rangle}_{All}(T_3)$ boundaries of the range of possible values T_{All} (experiment 2)

Figure 9 shows that the dependence $T_{All} = T_{All}(T_2)$ for experiment 1 can be approximated by a linear function $f(T_2) = 0.11 \cdot T_2 + 27.5$. Its values practically do not depend on T_2, since when changing T_2 from 1 to 9, this value changes from 27 to 27.9, i.e. no more than 3.4%.

Figure 10 shows that the dependence $T_{All} = T_{All}(T_2)$ for experiment 2 can be approximated by a linear function $\left(T_{all}(T_3) = 0.02 \cdot T_3 + 27.97\right)$ When changing T_3 from 10 to 19, this value changes from 27.8 to 27.5, i.e. no more than 1%.

V. Conclusion

Results of multichannel NQS simulation allow us to conclude that such macroscopic characteristics as the maximum queue length and the maximum waiting duration linearly depend on the moment of time at which the maximum input rate occurs.

From a practical point of view, this result means that if some part of the visitors does not rush immediately after the end of the event to exit gates, but enters the queue a little later, this strategy will reduce the maximum queue of the queue and the maximum duration of waiting in the queue.

As a result of the experiments, it can be concluded that visitors should be advised not to rush to leave immediately after the end of the match, since the length of the queue and, accordingly, the waiting duration in the queue will be shorter.

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