# Timed Petri Net Based Approach for Elevator Group Controls

Young Cheol Cho, Zavarin Gagov, and Wook Hyun Kwon

**Abstract**: In this paper, an optimal group control for elevator systems is proposed with timed Petri net based approach. Elevator system is modeled by timed Petri nets and hall call response times are estimated with moment generating functions (MGFs) method, which is applicable to real traffic patterns. Two assignment policies are proposed to satisfy the demands of passengers (i.e. hall/car calls) and to handle exceptional situations. In addition, optimal algorithms are implemented to minimize cost functions. The performances of the elevator system employing the proposed algorithms are compared with each others in ways of several performance measures by a computer simulation.

**Keywords**: elevator system, timed Petri nets, moment generating function, hall call response time, optimal group control

## I. Introduction

A large number of modern elevator systems have been installed in most high-rise buildings. Recently, building traffic patterns become more and more diversified and complicated as they have more various functions and intelligence. To satisfy demands of passengers and operate the system safely and efficiently, cooperative operation between cars in the system has been employed, called *elevator group control*. Its basic function is to coordinate a group of cars to quickly answer registered demands (i.e. hall calls). In general, the assignment of an appropriate car for the corresponding hall call is determined with the consideration of many factors.

The elevator group control can be viewed as a combination of online scheduling, resource allocation and stochastic control problems which are often handled at job-shop systems or automated manufacturing systems. In general, these systems imply behaviors of discrete event systems (DESs) with time properties. However, elevator systems are more hard to deal with than other systems, because the states of the system are dynamically changeable among huge state space and sensitively dependent on coming events which are unpredictable in many cases.

Especially, the traffic pattern, which is one of important state variables of the system, is difficult to identify during the real operational period, since different kinds of traffic patterns (i.e. up-peak traffic, down-peak traffic, inter-floor traffic, two-way traffic, etc.) appear simultaneously. Thus, many researchers have handled the elevator group control with heuristic or rule-based approach and developed elevator group controller using fuzzy logic, neural networks or knowledge-based expert systems [1]-[5].

Since an elevator group control using fuzzy rule-based reasoning was first introduced in the late 1980s [2], a large number of elevator systems have been based on fuzzy logic [3]. Though successful enhancement in the performance of the elevator system has been made with fuzzy group control, continuous research identified that by the lack of learning capabilities, it cannot improve the control algorithm under dynamic circumstances.

In order to solve the above problems, neural networks have been employed in the elevator group control and neural network-based controllers were developed with a performance criterion of minimizing hall call response time [4][6]. In addition, neural networks were used to select the appropriate traffic patterns so that the group controller could choose the best hall call assignment. However, this approach also has a weakness in that it takes efforts for detailed tuning of adaptive control and the convergence rate of online adaptation is not satisfactory as the authors remarked [4].

On the other hand, much research has been focused on the elevator group control using expert system-based methods or optimal control theories including `Dynamic zoning' [7][8], `Threshold-based dynamic programming' [9][10], `Channeling' [11], `Variance analysis' [12][13], `Blackboard architecture' methods [14] and etc. For example, dynamic zoning is an another method to make the controller adapt to some traffic patterns and threshold-based dynamic programming method provides an optimal solution during up-peak traffic mode. However, since most existing methods are derived within some limited situations, they perform well during particular traffic conditions but fail to be optimal during other traffic conditions. Thus, some proprietary and heuristic algorithms have been used for elevator group control in real practice by design engineers until now.

In this paper, timed Petri nets (TPNs) are used to describe the dynamic behaviors of elevator system. Petri nets are appropriate models to represent the behavior of DESs, because of their flexibility and visualization. There exists a large body of tools for qualitative and quantitative analysis of Petri nets [15]. The moment generating function method (MGF) has been successfully applied to timed Petri nets to analyze the performance of DESs [16]. Hall call response time is estimated by means of the reduction rules of MGF. In addition, we propose two assignment policies to minimize total response times and handle exceptional situations of the system which will perform well under different kinds of traffic patterns [17].

In Section II, we introduce timed Petri nets and moment generating function methods. In Section III, Some difficulties in elevator group control are explained and a TPN model of elevator system and then a reduced model is developed for the estimation of hall call response time. In Section IV, the simulation result for the online estimation of hall call response time is analyzed. In Section V, two assignment policies are

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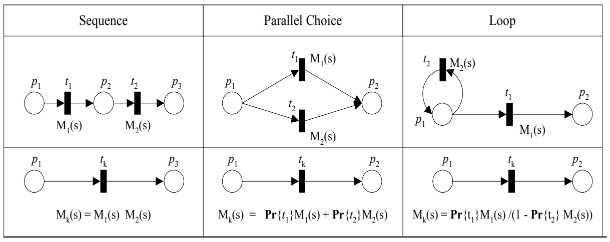
Table 1. Equivalent MGFs for three structures.




proposed and optimal algorithms are presented to minimize the cost functions related to the hall call response time. In Section VI, a computer-aided simulation tool is developed for the validation and evaluation of the proposed algorithm. Finally, a conclusion is remarked in Section VII.

## II. Timed Petri nets and MGFs

A timed Petri net model considered in this paper is a six-tuple $(P, T, W, m, B, F)$ where $P = \{p_1, p_2, \Lambda, p_n\}$ is a finite set of places, $T = \{t_1, t_2, \Lambda, t_s\}$ is a finite set of transitions, $W : (P \times T) \cup (T \times P) \rightarrow N$ is an arc function where $N = \{0,1,\Lambda\}$ and $m : P \rightarrow N$ is an marking whose *i*-th component is the number of tokens in the *i*-th places, $B : T \rightarrow [0..1]$ is a probability that transition can fire and $F : T \rightarrow R$ is a vector whose component is a firing time delay with a general distribution function. This paper follows traditional enabling rules and firing rules of previous literatures like [15][18].

Graphically, each place is depicted as a circle, and each transition is depicted as a bar, In TPNs, *immediate transitions* (i.e. transitions with zero firing time) are drawn as thin bars and *timed transitions* (i.e. transitions with non-zero firing time) as thick bars. Each arc function is represented by a directed arrow from *t* (or *p*) to *p* (or *t*) and a token in a place is represented by a dot.

Moment Generating Functions: Application of the moment generating functions (MGFs) concept has been presented in the graphical evaluation and review technique developed in the 1960's. Since it was proven that MGF approach is successfully applicable to the analysis of timed Petri nets in early 1990s, the timing performance of many stochastic DESs has been analyzed with MGFs. An MGF is defined as follows:

$$M(s) = \int_{-\infty}^{\infty} e^{st} f(t) dt \qquad (1)$$

where *s* is an extended parameter, and *f(t)* is a probability density function of random variable *t*. We can find *n*-th moment
by differentiating the MGF *n* times and setting *s*=0

$$\frac{\partial^n}{\partial^n s^n} M(s)|_{s=0} = E(t^n) \ . \qquad (2)$$

Reduction Rules: Three fundamental structures (series, parallel, and loop) can be reduced into a single transition in MGFs. The results of reduction rules are summarized in Table 1. In the first column of Table 1, $t_1$ with an MGF of $M_1(s)$ and $t_2$ with an MGF of $M_2(s)$ constitutes a sequence structure. They can be equivalent to one transition with $M_k(s)$ which is equal to the product of $M_1(s)$ and $M_2(s)$, i.e., $M_k(s) = M_1(s) \cdot M_2(s)$. In the second and third column in Table 1, parallel and loop structures are equivalent to one transition with MGFs of $M_k(s) = \Pr\{t_1\}M_1(s) + \Pr\{t_2\}M_2(s)$ and $M_k(s) = \Pr\{t_1\}M_1(s) \ /[1 - \Pr\{t_2\}M_2(s)]$ respectively, where $\Pr\{t\}$ is a probability that the transition *t* can fire. These reduction rules will be used to simplify the elevator model based on TPN.

## III. TPN-based modeling of elevator systems

The time taken for a car to serve a hall call is said to be the *hall call response time* (HCRT). Sometimes the journey time (HCRT + service time) is considered as a performance index [5]. However, the discomfort or irritation of passengers in the moving car is relatively small compared with that of the waiting passengers at the floor. The HCRT is related with many factors as follows: system environment (car numbers, total floors, etc.), current and future traffic demands, car dynamics (car contract capacity/speed, door opening/closing times), etc. Some factors such as system environment and car dynamics are deterministic and other factors are non-deterministic or difficult to predict exactly.

Using an example shown in Fig. 1, some difficulties of the estimation of HCRT and assignment decisions are demonstrated. Currently, Car A is moving up from 1st floor to serve a car call of 4-th floor (i.e. $c_4$) and to answer an assigned hall call with up direction at 2-th floor (denoted by $h_{up}^2$) and Car B is moving up to serve a car call (i.e. $c_{14}$). We suppose that a new hall call, $h_{up}^{10}$ occurs right now. Let's try to estimate which car can answer to $h_{up}^{10}$ faster.

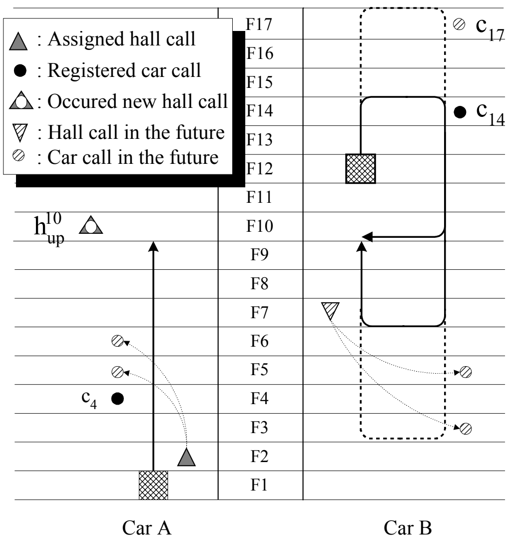



Fig. 1. An example of elevaotr group control.

Even taking into account the memorized demand $c_{14}$, Car B is physically closer to $h_{up}^{10}$ than Car A. Thus, it seems that

Car B can serve $h_{up}^{10}$ faster than Car A. If there is no another future demands, the observation is true. However, suppose that we have so called *down traffic* such that the probability to have hall calls with down direction is higher than the probability to have hall calls with up direction at given moment. Then, there is higher probability that a hall call of down direction (e.g. $h_{dn}^{7}$ ) will be assigned to Car B right after. By this hall call, the trajectory of Car B might become from a trajectory (shown by the solid line) to a longer one (shown by the dotted line). Obviously, in order to estimate car trajectory correctly, we should know some statistical data showing the probability to have hall/car calls at each floor, which is a difficulty related to the trajectory.

By the way, suppose that now the probability to have stop demands of up direction is significantly higher at lower floors (e.g. there are restaurants or shops). Such conditions will lengthen mainly the traveling time from 1st floor to 6-th floor (e.g. $h_{up}^{2}$ of Car A generates $c_5$ and $c_7$ ). Though the trajectory of Car A has no change, its hall call response time can be affected most significantly, which is another difficulty related to the stop demands.

In addition, there is a difficulty related to system dynamics itself. Suppose that by a nice assignment algorithm, the hall call $h_{up}^{10}$ has been assigned to Car B. After that, a car call demand, $c_{17}$ occurs at top floor before Car B reaches to 14-th floor. Hence the physical distance from Car B to $h_{up}^{10}$ becomes 3+3 floors longer. Obviously the hall call $h_{up}^{10}$ , which has been already assigned to Car B, should be released from Car B and re-assigned to Car A.

Then, we can finally conclude with the consideration of above difficulties that 1) the car trajectory depends nonlinearly on traffic patterns, 2) HCRTs are related significantly with stop demands until the service of the hall call and 3) if a hall call is not properly assigned due to new car calls or hall calls, a re-assignment mechanism is needed.

### III. 1 Notations and passage concept

Table 2. Notations for elevator model.

| Symbol | Description |
|---|---|
| $N$ | total number of floors served |
| $L$ | number of cars in the system |
| *E.pos* | current position of the *i*-th car |
| *E.dir* | the direction of the *i*-th car |
| $c_n$ | Car call demand at *n*-th floor |
| $h_{dir}^{n}$ | hall call demand of `*dir*' direction at *n*-th floor |
| $C$ | car call set of a car |
| $H$ | hall call set of a car |
| $W_i(h)$ | HCRT of a hall call *h* for the *i*-th car |

We introduce some notations at Table 2 for the remainder of the paper. Generally, assigned hall calls of the *i*-th car can be classified into three classes according to its direction and position as follows: (Simply, we derive equations when a car is moving up.)

$$H = H_F \cup H_S \cup H_T$$

where,
$H_F = \{h_{dir}^{floor} \in H \mid dir = (E.dir \,\|\, stop)\ and\ floor > E.pos\}$ and $H_S = \{h_{dir}^{floor} \in H \mid dir \neq E.dir\}$ and $H_F = \{h_{dir}^{floor} \in H \mid dir = E.dir\ and\ floor \leq E.pos\}$ are called the first passage, second passage, third passage assigned hall call set respectively.

First passage hall call set includes hall calls which can be served by the car along the right direction and the second passage hall call set includes hall calls which must be served along opposite direction after the car serves the first passage hall call set. Any hall call is included in one of three classes of $H_F$ , $H_S$ and $H_T$ . Without an exceptional situation, hall calls of $H_F$ have higher priority than hall calls of $H_S$ and $H_T$ and hall calls of $H_S$ have higher priority than hall calls of $H_T$ in service order. The service of hall calls in $H_F$ is little interfered by coming events (i.e. hall calls or car calls), but the service of hall calls in $H_S$ and $H_T$ is much interfered by coming events. By classifying all the hall calls into three passages, HCRTs can be estimated more systematically and efficiently.

### III. 2 System model

At first, it is necessary to present traditional constraints on the behavior of a car for the modeling of the system as follows:

*A.1* A car must not pass a floor at which a passenger wishes to alight.

*A.2* A car must not reverse direction with passengers in the car.

*A.3* A car must stop only at demanded floors (car or hall calls).

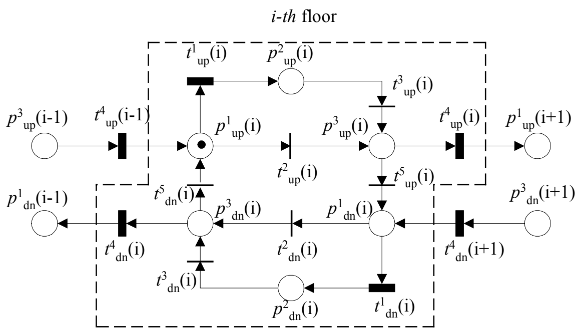



Fig. 2. A TPN model of an elevator car.

Table 3. Descriptions of places and transitions in Fig. 2.

| Nodes | Description |
|---|---|
| $p_{up}^{1}(i)$ | a car arriving at *i*-th floor with up direction |
| $p_{up}^{2}(i)$ | a car serving hall/car calls at *i*-th floor |
| $p_{up}^{3}(i)$ | a car departing at i-th floor with up direction |
| $t_{up}^{1}(i)$ | a car starts to serve hall/car calls at *i*-th floor |
| $t_{up}^{2}(i)$ | a car transits *i*-th floor |
| $t_{up}^{3}(i)$ | a car finishes to serve hall/car calls *i*-th floor |

| | |
|---|---|
| $t_{up}^{4}(i)$ | a car starts to depart *i*-th floor to (*i+1*)-th floor |
| $t_{up}^{5}(i)$ | a car starts to move to down direction |

*A.4* A car must not accept passengers for the reverse direction of travel.

Fig. 2 shows a TPN model at *i*-th floor of elevator system. A token in a place represents the current position of a car. The transitions depicted by thick bars mean that its firing requires some delay and the transitions depicted by thin bars mean immediate transitions.

Table 3 describes the meanings of places and transitions in Fig. 2. The token in $p_{up}^{1}(i)$ moves to $p_{up}^{3}(i)$ according to the constraint *A.4* with no time delay. Otherwise, the token in $p_{up}^{1}(i)$ moves to $p_{up}^{3}(i)$ with a firing time delay (passengers loading/unloading + door open/closing time) according to the constraints *A.1* and *A.3*. In general, the firing times of $t_{up}^{1}(i)$ and $t_{dn}^{1}(i)$ are non-deterministic and dependent on passengers' traffic. But it is reasonable by experimental bases to assume that its stochastic distribution is exponential and the MGF is already known as $\lambda_t^{-1}/(\lambda_t^{-1}-s)$ where $\lambda_t^{-1}$ is the average firing time of a transition *t*. The firing time delay of $t_{up}^{4}(i)$ or $t_{dn}^{4}(i)$ means the transit time between two floors which may be deterministic decided by car dynamics. The transition probability of a transition t, $\Pr\{t\}$, satisfies that

$$\sum_{t\in^{\bullet}p}\Pr\{t\}=1 \tag{4}$$

for any place $p\in P$.

In the system model of Fig. 2, we can observe that $\Pr\{t_{up}^{2}(i)\}=1-\Pr\{t_{up}^{1}(i)\}$, $\Pr\{t_{dn}^{2}(i)\}=1-\Pr\{t_{dn}^{1}(i)\}$ for any *i*, and $\Pr\{t_{up}^{4}(i)\}=1-\Pr\{t_{up}^{5}(i)\}$, $\Pr\{t_{dn}^{4}(i)\}=1-\Pr\{t_{dn}^{5}(i)\}$ for $1 < i < N$. According to the elevator behavior at boundary floors, $\Pr\{t_{up}^{5}(N)\}=\Pr\{t_{dn}^{5}(1)\}=1$ where minimum floor=1, maximum floor= *N*.

In general, the transition probabilities are dependent on the state of the corresponding car. The state of a car consists of current position (= $E_i.pos$), direction (= $E_i.dir$), registered car call set (=*C*), assigned hall call set (=*H*). Especially, the transition probabilities are tightly coupled with *C* and *H*, because new car calls can occurs when a car answers an assigned hall call.

We assume that it is known the probability that a new car call at *j*(>*i*)-th floor occurs by the hall call $h_{up}^{i}$, which is denoted by $\Pr\{cc=j\mid h_{up}^{i}\}$. In practice, this probability can be obtained by statistic data gathered from a group controller in elevator system, which will be explained in more detail at Section IV. For down direction, we also assume that $\Pr\{cc=j\mid h_{dn}^{i}\}$ is known. According to the constraint *A.3*, we can obtain

$$\Pr\{t_{up}^{1}(i)\}=\Pr\{\text{car stops at } i\text{ - th floor}\}=\begin{cases}1 & \text{if } h_{up}^{i}\in H \text{ exists or } i\in C\\ \Pr\{cc=i\mid H\} & \text{otherwise.}\end{cases} \tag{5}$$

It will be shown in next section that $\Pr\{cc=i\mid H\}$ is calculated with $\Pr\{cc=j\mid h\}$ for each $h\in H$. In addition, $\Pr\{t_{dn}^{1}(i)\}$ can be obtained similarly.

$\Pr\{t_{up}^{4}(i)\}$ is a probability that a car serves hall calls or car calls demanded at more than *i*-th floor. It is obtained recursively by the following equation:

$$\begin{aligned}\Pr\{t_{up}^{4}(i)\} &= \Pr\{\textbf{A car serves hall/car calls at more than } i\textbf{ - th floor}\}\\ &= \mathbf{Pr}\{cc\geq i+1\mid H,C\}\\ &= \mathbf{Pr}\{cc\geq i+1\mid H,C\}+\mathbf{Pr}\{cc\geq i+2\mid H,C\}\\ &\quad -\mathbf{Pr}\{cc\geq i+1\mid H,C\}\times\mathbf{Pr}\{cc\geq i+2\mid H,C\}\\ &= \mathbf{Pr}\{t_{up}^{1}(i+1)\}+\mathbf{Pr}\{t_{up}^{4}(i+1)\}\\ &\quad -\Pr\{t_{up}^{1}(i+1)\}\times\mathbf{Pr}\{t_{up}^{4}(i+1)\}.\end{aligned} \tag{6}$$

$\Pr\{t_{dn}^{4}(i)\}$ is also calculated similarly.

$\tau[p,p']$ for $p,p'\in P$ and is defined as the time delay which it takes for a token in the TPN model to reach $p'$ from starting $p$ place. When the starting place $p$ is the current position of a car and the target place is the $p_{dir}^{1}(i)$ at *i*-th floor where a hall call $h_{dir}^{i}$ is registered, $\tau[p,p']$ is equivalent to hall call response time of $h_{dir}^{i}$ (i.e. $\tau[p,p']=W(h)$). Then, the mean value of $\tau[p,p']$ can be calculated by the moment generating function between two places through Eq. (2).

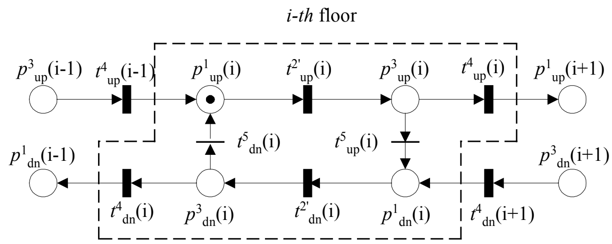


Fig. 3. Reduced TPN model.

In order to obtain HCRTs more efficiently, we present a reduced TPN model by means of the reduction rules of MGFs. Since the structure between $p_{up}^{1}(i)$ and $p_{up}^{3}(i)$ (or $p_{dn}^{1}(i)$ and $p_{dn}^{3}(i)$) is parallel, we can reduce it into a single transition $t_{up}^{2'}(i)$ (or $t_{dn}^{2'}(i)$) with a MGF $\Pr\{t_{up}^{1}(i)\}\times M(t_{up}^{1}(i))$ (or $\Pr\{t_{dn}^{1}(i)\}\times M(t_{dn}^{1}(i))$. Figure 3 shows the reduced TPN model of Fig. 2. By the reduced model, we can simply calculate the MGF between arbitrary two places.

**Lemma 1:** Given a car located at *i*-th floor with up direction and its assigned hall call set $H=H_F\cup H_S\cup H_T$, the probability $\Pr\{t_{up}^{4}(k)\}$ at *k*-th floor is as follows:

(a). If $h_{up}^{j}\in H_F$, $\Pr\{t_{up}^{4}(k)\}=1$, for $i\leq k<j$ (7)

(b). If $h_{dn}^{j}\in H_S$, $\Pr\{t_{up}^{4}(k)\}=1$, for $i\leq k<j$ and (8)

$\Pr\{t_{dn}^{4}(k)\}=1$, for $j<k\leq N$, (9)

(c). If $h_{up}^{j}\in H_T$, $\Pr\{t_{dn}^{4}(k)\}=1$, for $j<k\leq N$ and (10)

$\Pr\{t_{up}^{4}(k)\}=1$, for $1\leq k<j$. (11)

**Proof:** (a) Since a car must stop at *j*-th floor according to the constraint *A.3*, $\Pr\{t_{up}^{1}(i)\}=1$. Then, $\Pr\{t_{up}^{4}(k)\}=1$ for $k=i,\Lambda,j-1$ by Eq. (6). (b) Let $j_F^{*}$ be $\max\{n\mid j_{up}^{n}\in H_F\}$. If $H_F\neq\Theta$ and $j_F^{*}<j$, $\Pr\{t_{up}^{4}(k)\}=1$ for $i\leq k<j_F^{*}$ by

Lemma 1.a. Then the next hall call for the car to serve is an second passage hall call $h \in H_S$ according to *A.2*. Also, $\Pr\{t_{up}^4(k)\}=1$ for $j_F^* \le k < j$ by the constraint *A.3*. If $H_F = \Theta$, the first hall call for the car to serve is one of the second passage hall calls at $j_S^*$-th floor where $j_S^*$ be $\max\{n \mid j_{dn}^n \in H_S\}$. Thus, $\Pr\{t_{up}^1(j_S^*)\}=1$. $\Pr\{t_{up}^4(k)\}=1$ for $k = i, \Lambda, j-1 \le j_S^*$ by Eq. (6). In addition, $\Pr\{t_{dn}^1(j)\}=1$ by the constraint *A.3* and $\Pr\{t_{dn}^4(i+1)\} = \Pr\{t_{dn}^1(i)\} + \Pr\{t_{dn}^4(i)\} - \Pr\{t_{dn}^1(i)\} \times \Pr\{t_{dn}^4(i)\}$ Thus, $\Pr\{t_{dn}^4(k)\}=1$ for $k = j+1, \Lambda, N$.
(c) By Lemma 1.a, Eq. (11) is proved and by Lemma 1.b, Eq. (10) is proved. ■

Lemma 1: mentions that the car *must* move to the floor where hall call are registered and *must not* change its direction before the service. The above lemma is extended similarly in that a car move down direction. By Lemma 1, some transitions with zero transition probabilities (i.e. $t_{up}^5(i)$ and $t_{dn}^5(i)$) are removed from the reduced TPN model in Fig. 3. Using the reduction rules of MGF method and properties of transition probability from Lemma 1, the MGF of hall call response time between an assigned hall call and a corresponding car is calculated as follows:

Lemma 2: Let a token be located at $p_{up}^3(i)$ with no firing time delay. Then, the moment generating function between $p_{up}^3(i)$ and an assigned hall call $h \in H$ is as follows :

(a). If $h_{up}^j \in H_F$,

$$M(\tau[p_{up}^3(i), p_{up}^1(j)]) = \prod_{k=i}^{j-1} M(t_{up}^4(k)) \cdot \prod_{k=i+1}^{j-1} M(t_{up}^2(k)) \quad (12)$$

(b-1). If $h_{dn}^j \in H_S$ and $j > i$,

$$M(\tau[p_{up}^3(i), p_{dn}^1(j)]) = M(\tau[p_{up}^3(i), p_{up}^1(j)]) \cdot M(t_{up}^2(j)) \cdot \left[\sum_{k=j}^{N} 1 - \Pr\{t_{up}^4(k)\} \prod_{l=j}^{k-1} \Pr\{(t_{up}^4(l)\} A(l)\right] \quad (13)$$

(b-2). If $h_{dn}^j \in H_S$ and $j \le i$,

$$M(\tau[p_{up}^3(i), p_{dn}^1(j)]) = M(\tau[p_{dn}^3(i), p_{dn}^1(j)]) \cdot M(t_{up}^2(j)) \cdot \left[\sum_{k=i}^{N} 1 - \Pr\{t_{up}^4(k)\} \prod_{l=i}^{k-1} \Pr\{(t_{up}^4(l)\} A(l)\right] \quad (14)$$

where, $A(l) = M(t_{up}^4(l)) M(t_{up}^2(l+1)) M(t_{dn}^2(l+1)) M(t_{dn}^4(l+1))$ and $\Pr\{t_{up}^4(N)\} = 0$.

(c). If $h_{up}^j \in H_T$,

$$M(\tau[p_{up}^3(i), p_{up}^1(j)]) = M(\tau[p_{up}^3(i), p_{dn}^1(j)]) \cdot M(t_{dn}^2(j)) \cdot \left[\sum_{k=1}^{j} 1 - \Pr\{t_{dn}^4(k)\} \prod_{l=k+1}^{j} \Pr\{(t_{dn}^4(l)\} B(l)\right] \quad (15)$$

where, $B(l) = M(t_{dn}^4(l)) M(t_{dn}^2(l-1)) M(t_{up}^2(l-1)) M(t_{up}^4(l-1))$ and $\Pr\{t_{dn}^4(1)\} = 0$.

## IV. Online estimations

For the calculation of HCRTs, the most important input data are the traffic patterns which is represented by $\Pr\{cc = j \mid h\}$ in this paper and the number of passengers. Traffic patterns are rapidly changing and dynamic. In previous literatures, traffic patterns have been classified into some classes such as up-peak, down-peak, inter-floor, etc.

There were different ways to identify these traffic patterns [19][20]. One way is the employment of artificial neural networks that continuously monitor the elevator system [19]. In most group controllers in practice, appropriate optimal policies are adopted according to the current recognized patterns. However, we need not to recognize the traffic patterns, because $\Pr\{cc = j \mid h\}$ is simply obtained by processing past traffic data in an operation interval.

Table 4. Origin/destination distribution (Inter-floor traffic).

| Origin Floors | Destination Floors ( $=K_c(i,j)$ ) | | | | | | | | | | | | # of Hall Calls $= K_h(dir,i)$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | UP | DN |
| 1 | . | . | 1 | 2 | . | . | 5 | 10 | 3 | . | 8 | 15 | 18 | . |
| 2 | 1 | . | . | 1 | 4 | 3 | . | 6 | . | 4 | . | 6 | 10 | 1 |
| 3 | . | . | . | 2 | . | 5 | 7 | 12 | 4 | 1 | 4 | 11 | 12 | . |
| 4 | 4 | 2 | . | . | . | 2 | . | 8 | 2 | . | 2 | 6 | 9 | 4 |
| 5 | 6 | . | 2 | . | . | . | 3 | 4 | 5 | 5 | 1 | 4 | 7 | 8 |
| 6 | 8 | 5 | 4 | 3 | . | . | . | 1 | . | . | 3 | 2 | 5 | 10 |
| 7 | 9 | 3 | . | 2 | . | . | . | . | . | . | . | 2 | 4 | 12 |
| 8 | 8 | 5 | 6 | . | 4 | 2 | . | . | . | . | . | 1 | 2 | 15 |
| 9 | 10 | . | 7 | 5 | 7 | 3 | 1 | . | . | . | . | . | 5 | 9 |
| 10 | 8 | 5 | 3 | 7 | . | 6 | 2 | 1 | . | . | . | . | 2 | 11 |
| 11 | 9 | 4 | 8 | 5 | 8 | . | . | 3 | 1 | . | . | . | 1 | 10 |
| 12 | 6 | 3 | 10 | 6 | 3 | . | 5 | . | 2 | 2 | . | . | . | 9 |

Table 4 shows traffic data gathered during an inter-floor traffic period. Each element in Table 4 represents the occurrence number of car calls from *i*-th floor to *j*-th floor denoted by $K_c(i,j)$ and the occurrence number of hall calls at *i*-th floor denoted by $K_h(UP,i)$ and $K_h(DN,i)$ for each direction respectively. By Table 4, we can estimate the probability $\Pr\{cc = j \mid h_{dir}^i\}$ for all *i* and *dir* = *UP, DN* as follows:

$$\Pr\{cc = j \mid h_{dir}^i\} = \frac{K_c(i,j)}{K_h(dir,i).} \quad (16)$$

Now, $\Pr\{cc = j \mid H\}$ can be easily calculated online with each conditional probability. When a hall call *h* is newly assigned to a car with an assigned hall call set *H*,

$$\begin{aligned}\Pr\{cc = i \mid H \cup \{h\}\} &= \Pr\{cc = i \mid H\} + \Pr\{cc = i \mid h\} \\ &\quad - \Pr\{cc = i \mid H\} \cdot \Pr\{cc = i \mid h\}.\end{aligned} \quad (17)$$

When a hall call *h* is already served,

$$\Pr\{cc = i \mid H - \{h\}\} = \frac{\Pr\{cc = i \mid H\} - \Pr\{cc = i \mid h\}}{1 - \Pr\{cc = i \mid h\}}. \quad (18)$$

On the other hand, the number of passengers loaded in the car or waiting at each floor should be identified to estimate exact HCRTs. These two variables are possible to measure in real group control systems without additional expensive measuring devices. Other timing factors such as current position of a car and door open/closing time should be considered in real group control systems. However, this paper approximates these values to be uniform at all floors. It will be shown that this approximation is reasonable for the estimation of HCRTs and optimal group controls in next section.

Fig. 4 shows the simulation result of HCRTs using the MGF method for some traffic patterns (i.e. up traffic, down traffic, inter-floor traffic). The test has been performed on a twenty-floor building model with a elevator system of the following specifications; number of cars ($L$): 4, average time to service a car call or hall call: 6 sec, transit time between two floors: 1.5 sec. In addition, the simulation result is obtained in two kinds of traffic burdens (i.e 150, 210 persons/5 min.) for each traffic pattern.

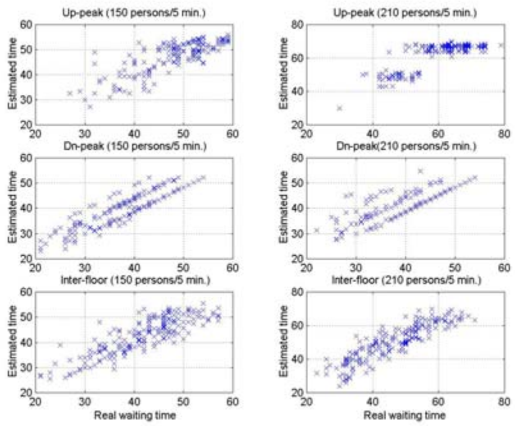



Fig. 4. Simulation result for the estimation of HCRTs.

We can see that the estimation is enough valid for various traffic patterns and the number of passengers (heavy/low). Especially, the estimated value is closely related to the real value in inter-floor traffic (i.e. mixed traffic) which occurs often in complex and multi-objective buildings.

## V. Optimal group controls

We present an optimal group control to enhance the performance of elevator systems. Given the assigned hall call set $H_i$ for the $i$-th car, $i \in [1..L]$, the performance index of system is determined by total summation of HCRTs

$$W_T = \sum_{h \in H_T} W(h \mid g), \tag{19}$$

where $g$ represents a policy of elevator group control and $H_T = \cup_{i=1}^{L} H_i$. The control policy $g$ is replaced with $H_i$ because a policy is equivalent to mapping all occurred hall calls to an optimal car. Since the HCRT is dependent only on the assigned hall call set of that car, not on those of other cars, Eq. (19) is changed into

$$W_T = \sum_{i=1}^{L} \{\sum_{h \in H_i} W(h \mid H_i)\}. \tag{20}$$

Let the assigned hall call set for the $i$-th car under the optimal policy be $H_i^*$ such that

$$W_T^* = \sum_{i=1}^{L} \{\sum_{h \in H_i^*} W(h \mid H_i^*)\} \le \sum_{i=1}^{L} \{\sum_{h \in H_i} W(h \mid H_i)\}. \tag{21}$$

There can be many optimal or sub-optimal policies for reducing the total response time according to employed control policies. In this paper, we consider two control policies. One is a policy that hall calls already assigned to a car can never be re-assigned by the occurrence of new hall calls. The other is a policy that assigned hall calls can be cancelled and again re-assigned to another car. The first policy is called *no cancellation policy* (NCP) and the second policy is called *re-assignment policy* (RAP). These two policies have been derived with the consideration of passengers' psychological feeling. In other words, NCP is necessary and widely used in real system, because the cancellation of assigned hall calls will cause passengers' displeasure, but there can be exceptional situations (e.g. car failure, fully-loaded car and long-time stop) such that assigned hall calls cannot served inevitably by the corresponding car. Then RAP is applied to re-assign affected hall calls under these exceptional situations.

### 1. No Cancellation Policy (NCP)

In NCP, a new hall call $h_{new}$ can be assigned to any car. The optimal assignment of $h_{new}$ given $H_i^*$ is simply to add the new hall call to one of existent assigned hall call sets without any re-assignments of existent hall calls. The increment of total HCRTs for each car is investigated under an assumption that the new hall call be assigned to the car. Let the incremental value of HCRTs for the $i$-th car be

$$\Delta W_i(h_{new}) = \sum_{h \in H_i^* \cup \{h_{new}\}} W(h \mid H_i^* \cup \{h_{new}\}) - \sum_{h \in H_i^*} W(h \mid H_i^*). \tag{22}$$

Then, we find

$$i_{opt} = \arg\left[\min_{i \in [1..L]} \Delta W_i(h_{new})\right] \tag{23}$$

and the new optimal policy is

$$g^* = \begin{cases} H_i^* \leftarrow H_i^* \cup h_{new} & \text{for } i = i_{opt} \\ H_i^* \text{ is reserved.} & \text{for } i \ne i_{opt} \end{cases}. \tag{24}$$

Since it is well known the impatience of passengers waiting a car increases exponentially when the waiting time exceeds a threshold time $t_H$ (e.g $t_H = 60$ sec) [21], we introduce an NCP with the consideration of hall calls exceeding $t_H$ called NCP-THT. The cost function considering the threshold time is determined by the following equation

$$\Delta W_i(h_{new}) = \sum_{h \in H_i^* \cup \{h_{new}\}} W_{t_H}(h \mid H_i^* \cup \{h_{new}\}) - \sum_{h \in H_i^*} W_{t_H}(h \mid H_i^*)$$

where,

$$W_{t_H}(h \mid H_i) = \begin{cases} W(h \mid H_i) & \text{if } W(h \mid H_i) \le t_H \\ w \times W(h \mid H_i) & \text{else if } W(h \mid H_i) > t_H,\ w > 1 \end{cases}.$$

The advantages of the NCP are that the confusion or bore of the waiting passengers can be reduced by immediate pre-reporting of the car coming near the target floor and the assignment algorithm is simple and that the computation burden of an implemented algorithm is small. However, the NCP overlooks more optimal policies which can be obtained by means of re-assignment of hall calls and the possibility of reducing the mis-reporting rate[1]

### 2. Re-Assignment Policy (RAP)

The assignment of $h_{new}$ in NCP or in exceptional situations

1) The rate that the information indicated to passengers on landing floor by LED display panels is mis-matched with the car actually arriving at the floor.

can affect response times of the hall calls previously assigned. Thus, the affected hall calls should be re-assigned to gain good performance. The affected hall call set for *i*-th car, given new hall call $h_{new}$, is denoted by $H_i^a(h_{new})$ and the unaffected hall call set is denoted by $H_i^{ua}(h_{new})$. Then, the re-assignment of affected hall call sets of one car affects the assigned hall calls of another cars.

Algorithm 1 is presented to minimize $W_T$ under the RAP. In addition, the RAP is extended with the consideration of a threshold time called re-assignment policy with threshold time called RAP-THT. Algorithm 1 guarantees that it finishes the procedure quickly in a finite loop, since the procedure uses the information of $H_i^*$ which is already optimally arranged by itself. Also, the computation burden is largely reduced by re-use of the value of $W(h \mid H_i^*)$.

Note that the RAP is not the unique optimal policy, which means it is a sub-optimal policy and there can be more optimal other policies. But, the optimal feature of RAP is somehow guaranteed by the adoption of NCP. By this fact, the solutions of the RAP are obtained with a small number of loops in many cases.

Algorithm 1: Re-Assignment Algorithm of RAP

Step 1 : Find $i_{opt} = \arg\left[\min_{i \in [1..L]} \Delta W_i(h_{new})\right]$

Step 2 : $H_{i_{opt}}^* \leftarrow H_{i_{opt}}^{ua}(h_{new}) \cup \{h_{new}\}$ and $H_A \leftarrow H_{i_{opt}}^a(h_{new})$

Step 3 : Select a hall call $h' \in H_A$.

Step 4 : Find $i_{opt} = \arg\left[\min_{i \in [1..L]} \Delta W_i(h')\right]$

Step 5 : $H_{i_{opt}}^* \leftarrow H_{i_{opt}}^{ua}(h') \cup \{h'\}$ and $H_A \leftarrow H_{i_{opt}}^a(h') - \{h'\}$

Step 6 : If $H_A$ is empty, stop the procedure,
Else goto step 3.

## VI. Simulation

To analyze and simulate the proposed optimal policies, a computer-aided simulation tool called ESES-Tool is developed. The input of the simulation stage of ESES-Tool is listed in Table V. Especially, the hall call and car call bank division is necessary to divide the normal service area and express service area, because many modern buildings are employing the bank division options.

Table 5. Input items for elevator simulation.

| Items | Description |
|---|---|
| Building Data | Number of floors, height, Number of cars in each group. |
| Traffic Data | Population, Concentration, Riding/ alighting time, traffic patterns. |
| Car Dynamics Data | Max Speed, Max acceleration, Jerk, door access time |
| System Options | Hall call/car call bank division, group control algorithm options. |

To reduce the simulation time under various system options, we adopt event-driven simulation method where system behaviors are classified with a number of events and states [22]. The transitions between the states are determined by the condition of current state. In the simulation kernel, Event scheduler manages the list of events in the order of its occurrence time. The traveling time between two floors is calculated based on the Molz' formulae of ideal lift kinematics [23]

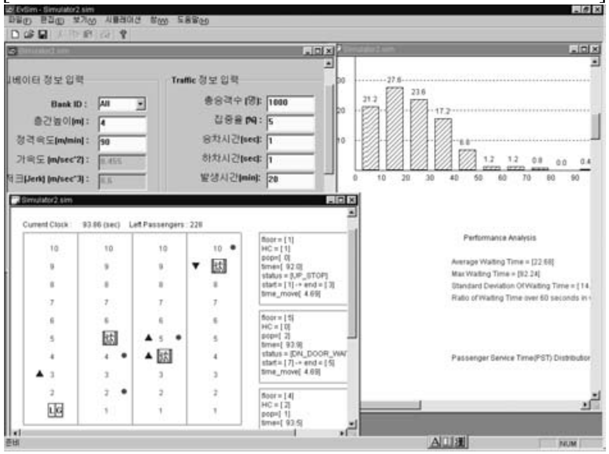



Fig. 5. A window of computer-aided elevator simulation tool.

which enable minimum travel times, taking to account maximum values of jerk, acceleration and speed. If the traveling distance is too short for the elevator contract speed or acceleration given at the simulation input stage, the maximum speed and acceleration attained during the trip may be calculated.

In addition, the ESES-tool supports both visual animation mode and quick time mode. In visual animation mode we can validate the correctness by eyes and, in quick time mode, we can obtain the results promptly without visualization delay. The result of the simulation stage contains many performance indices as follows: passenger service time, passenger journey time, hall call response time (HRT), long-HRT, etc. After simulation, the information is recorded in files. The another advantage of simulation stage is that we can compare several group control algorithms with standard reference algorithms and analyze each control algorithm. We implemented three reference algorithms called worst distance assignment (WDA), minimum sum assignment (MSA) and load balance assignment (LBA). Figure 5 shows a captured window of ESES-Tool.

Fig. 6 shows the simulation results of HCRTs by the NCP and NCP-THT policies. The test have been performed on a twenty-floor building model with the same specifications as Section IV and the weight *w = 2*. By Fig. 5, the NCP shows better performance than the previous policy which has been developed in LG Industrial Co. under different kinds of traffic patterns and the NCP-THT shows even better performance in that hall calls whose response times exceed $t_H = 60$ sec are greatly reduced. Figure 7 shows mean and maximum values of HCRTs under the RAP and RAP-THT when the configuration of the simulation is same as that of Fig. 6. Compared with the previous policy employed on GNI-2000 elevator system of LG-Otis, both the mean values and maximum values of HCRTs in various traffic patterns are enhanced by the RAP and the RAP-THT. Especially, the RAP-THT has better performance in heavy traffics than RAP, NCP and NCP-THT. Though the immediate pre-reporting can not achieved by RAP, the rate of mis-reporting is also reduced as shown in Fig. 8. The drawbacks of RAP and RAP-THT are that the required computation is larger and the timing of pre-reporting by RAP and RAP-THT is later than NCP or NCP-THT. But, the computational issue can be overcome with feasible solutions such as the high-speed computer control systems and the time of pre-reporting can be improved by the appropriate combination of both NCP and RAP policies.

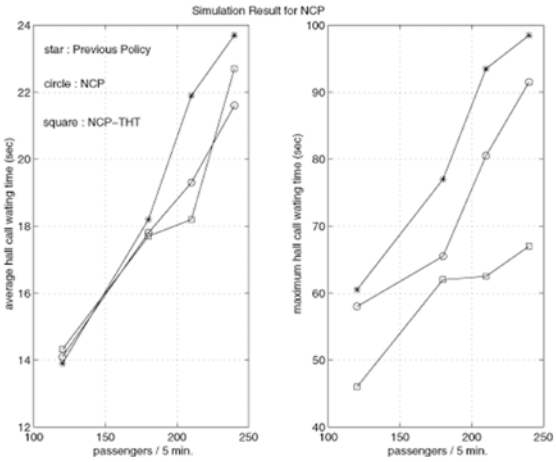



Fig. 6. Simulation result of NCP and NCP-THT.

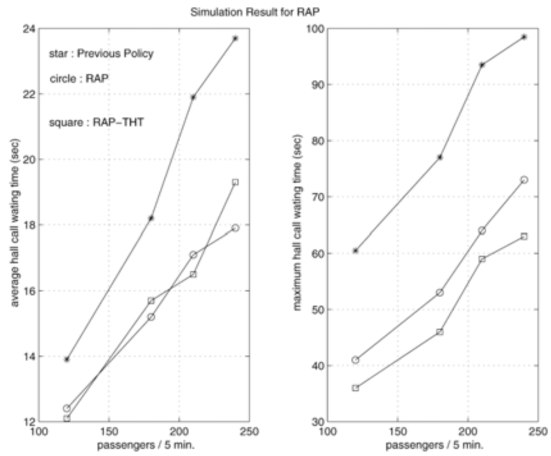



Fig. 7. Simulation result of RAP and RAP-THT.

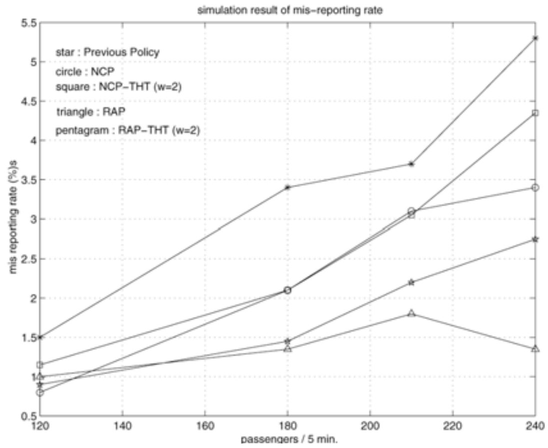



Fig. 8. Mis-reporting rates of NCP(-THT) and RAP(-THT).

## VII. Conclusion

In this paper, a timed discrete event modeling of hall call response time (HCRT) in elevator system and optimal group controls based on the estimation of HCRTs are proposed. Timed Petri net model and moment generating function (MGF) method are applied to estimate HCRTs efficiently in real operation. This estimation has been shown to be valid in various and dynamic traffic patterns by a computer simulation, even the case that several traffic patterns are mixed.

The two assignment policies are developed to reduce HCRTs and to cope with exceptional situations. By optimal algorithms developed for two assignment policies, average HCRTs and maximum HCRTs are much enhanced compared with the previous work. In this paper, we only used the first moment of MGFs for the estimation of HCRT. However, the second moment of MGFs can be used to reduce the mis-reporting rate because it helps determine the accuracy of HCRTs, which is another advantage of MGF method. Compared with traditional approaches such as fuzzy algorithm and neural networks, the proposed method may take less efforts for the tuning of adaptive control and the convergence rate of online adaptation is satisfactory.

In the future, it is necessary to implement the proposed assignment algorithms in real system and to research how two policies are combined to perform the fast pre-reporting as well as to handle exceptional situations in elevator systems.

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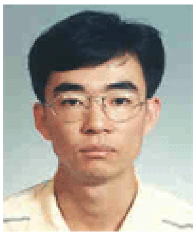

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