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RESEARCH ARTICLE - CIVIL ENGINEERING

Assessment of Passengers' Transfer Zones in the Transit Centers: A PH-Based State-Dependent Discrete-Event Simulation Framework

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Abstract

The passengers' transfer zone in the transit centers is the interface among various transportation modes, where passengers transfer from one mode to another. The Transit Cooperative Research Program (TCRP)-Report 165 presents the capacity analysis technique for the passengers' transfer zone in the transit centers. However, the TCRP-Report 165 procedure is based on the fixed values of passengers' arrival flow and service time of facilities, which do not depict the real scenario. To aid the designers of transit centers as well as to capture the randomness in the arrival flow and service time, a discrete-event simulation (DES) framework based on the PH-distributed random variates is developed. The DES framework represents the passengers flow in the transit centers and also takes into account the randomness in passengers' arrival flow and service time. Sensitivity analysis is conducted under different settings of passengers' arrival flow, coefficient of variation (CV) and dimensional features (length and width of transfer zone). The results showed that the passengers' arrival flow, CV and width of the transfer zones are highly influential parameters, while the length of transfer zones has no significant influence. Therefore, during the design phase of transit centers, emphasis should be given to influential parameters as they illustrate the actual conditions in the transit centers.

Keywords Transfer zones · Transit centers · PH-based discrete-event simulation · Queuing network · Sensitivity analysis

1 Introduction

The passengers' transfer zone in the transit centers is the interface among various transportation modes, where passengers shift from one mode to another. Integrated transportation systems have been executed in various parts of the world [1]. The degree with which transfer from one mode to another has been performed smoothly and safely will strongly influence the system acceptance. The inadequate design leads to the longer queues, congestions and disorientation of the passengers in the transit centers. Therefore, intermodality is a vital part of sustainable mobility, and adequate design of intermodal transfer zones is of utmost importance. The design parameters of intermodal transfer zones are required to be properly assessed to create a suitable environment for the transfer and processing of passengers [2].

The passengers' circulation requirements should be assessed prior to the design of transfer zones in the transit centers. The Transportation Research Board (TRB's) Transit Cooperative Research Program (TCRP)-Report 165 [3] provides the capacity analysis and design techniques for the passengers' circulation at the different transfer zones in the transit centers. These techniques involve comprehensive capacity analysis of passengers' circulation at the transfer zone by taking into account several controlling parameters, such as passengers' inter-arrival time, passengers' walking speed, traffic density and the sizes (length and width) of the transfer areas. However, analysis and design techniques based on TCRP-Report 165 have several shortcomings. The TCRP-Report 165-based techniques assume that the passengers' inter-arrival time at the entrance of the transfer area is a fixed value at different instants, while in reality the fluctuation exists in

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the
passengers' arrival flow. The TCRP-Report 165-based capacity analysis and design techniques also assume that the passengers' walking speed in the transfer area is constant and the interaction with the surrounding passengers is ignored. In reality, the passengers' walking speed in the transfer area is a function of the number of passengers present. The passengers' walking speed decreases with an increase in the number of passengers, which affects the passengers' dwell time in the transfer area and the phenomenon is known as state dependence. The consequence of these shortcomings is the inadequate design that causes blockage of passengers' flow during peak and off-peak hours.

Furthermore, several studies [4–6] reveal that, among various design parameters that affect the performance of passengers' passageways, the width is considered as an important one. The width computation by using the TCRP-Report 165 technique involves the fixed value of passengers' arrival flow divided by the fixed value of service rate per unit width of passengers' transfer area. This deterministic behavior of arrival flow and service rate is analogous to the deterministic-based $D/D\,(n)/N/N$ queuing modeling technique. But in reality, the passengers' flow in the transit centers is highly random.

Several researchers have also performed analysis and design of transit facilities by taking advantage of the queuing analysis technique. Stochastic analytical models with consideration to passengers' fluctuation factors were developed [4,7]. But the drawback of these models is the complications associated with the closed-form solution of explicit mathematical expression. The models are based on quasi-birth–death processes (iteration-based) [8], and the computational complexity depends on the number of passengers in the facility. The computational complexity enhances as the number of passengers increases. The complexity further increases when a model for single facility extends to the network of facilities (for example, network of stairways and passageways).

In contrast to the stochastic analytical modeling technique, the discrete-event simulation (DES) modeling is an efficient technique that simultaneously takes advantage of the queuing systems as well as eliminating the need to solve explicit mathematical expressions [9,10]. Therefore, in this research, we limit our scope of study to the passengers' flow in intermodal passengers' transfer zones from the metro rail transit (MRT) station to the bus terminal and taxi stop. The passengers' circulation in the form of a stairways and passageways network is considered only, while the circulation via elevator or escalators is not taken into account. Moreover, the sensitivity analysis technique is adopted to assess the performance of various design parameters of passengers' transfer areas such as passengers' arrival rate, coefficient of variation (CV), length and width of the transfer zone. In order to consider the fluctuation in passengers' flow as well as service fluctuation, the phase-type (PH) probability distribution is used to fit the passengers' arrival rate and service time of passengers' transfer zone.

The rest of the paper features a discussion on the queuing network representation of the intermodal transfer zone, which is followed by the PH distribution fitting to the passengers' inter-arrival time and state-dependent service time. A PH-based state-dependent DES model is developed to obtain the performance measures and perform the sensitivity analysis based on the results. Finally, comparison is made with other existing techniques, and conclusions are drawn from the research findings.

2 Literature Review

Considerable efforts have been put forward by the researchers in developing the capacity analysis techniques for the pedestrian as well as vehicular transportation hubs. Due to the lack of high-speed computing technologies and sophisticated simulation modules even in the recent past, several researchers focused on developing analysis and design techniques based on the stochastic analytical queuing models.

In the early 1990s, Smith [11] developed an $M/G(n)/N/N$ analytical queuing model for the pedestrian facilities of commercial building. Mitchell and MacGregor Smith [12] analyzed and designed the different topologies of the pedestrian network. Cruz et al. [13] developed an $M/G(n)/N/N$ queuing network model for the capacity analysis as well as an optimal design of pedestrians' transfer zones. Woensel and Vandael [14] developed a multi-server, finite-capacity queuing networks model for the vehicular traffic on the roads. In the domain of MRT station facilities, Jiang et al. [15] developed an $M/G/1$ analytical queuing model for the performance assessment of passengers' flow in walkways of MRT station. Chen et al. [16] used an $M/G(n)/N/N$ analytical queuing network model to study the passengers' transfer zone evacuation capacity at the MRT stations. Xu et al. [17] have developed a capacity optimization method for the MRT station capacity optimization based on the $M/G(n)/N/N$ analytical queuing network model. Jiang et al. [18] developed an analytical queuing model for the performance assessment of MRT station elevator facility.

Simultaneously taking the advantage of queuing systems as well as eliminating the need to solve explicit mathematical expressions, several researchers developed the simulation models for the analysis of vehicular and pedestrian facilities. The facilities were first described as a queuing system and then translated into the DES models. For example, Lovas [19] developed a $G/M/1$ DES evacuation model for the analysis and design of the pedestrian facility in buildings. Cruz et al. [20] developed an $M/G(n)/N/N$ state-dependent network simulation model. Khalid et al. [21] established an $M/G(n)/N/N$ discrete-event simulation (DES) model to study pedestrians' traffic flow in a queuing network system. However, the description of facilities in these researches still needs to be enhanced. These models are based on the exponential distribution which is limited to the conditions where the variance equals the mean.

Besides the DES modeling method, the micro-simulation models that are based on the social force model (SFM), lattice-gas model (LGM), cellular automata model (CAM), or other models are another widely used technique for the facilities analysis [22–26]. The microscopic simulation models are more detailed in depicting the real-world system or practical scenario as they illustrate the individual (passengers or vehicles) characteristics and their behaviors [27,28]. Similarly, the physical environment, such as the passengers' circulation areas, is also necessary in microscopic simulations. Due to these reasons, the microscopic simulation involves extensive calibration effort and large computational time. On the contrary, the DES model does not require the specific individual and physical environment; therefore, it is more efficient and simple to calibrate than the microscopic simulation models. It has a wide range of applications because of its accuracy and efficiency. Another advantage that makes the DES method superior than micro-simulation method is its convenient coupling with the optimization tool to develop a simulation–optimization framework. Several researchers also developed the mesoscopic DES models for the vehicular traffic on roads [29–35]. The distinct benefit of using mesoscopic simulation techniques is its fast, simpler and less involved creation of models that are easier to reconfigure than the microscopic simulation models.

To limit our research to the passengers' flow in transit centers, unfortunately, none of the researchers have so far analyzed and designed passengers' transfer zone in the transit centers as a queuing network system with the fluctuated passengers' arrival flow and state-dependence service time. To limit the scope of our research to passengers flow in transportation hubs as well as to consider the phenomenon passengers' flow fluctuation in the transit centers, we aim to develop a PH-based state-dependent DES model of passenger' circulation of the transfer zone in the *SimEvents*® simulation module, which considers passengers' arrival flow fluctuation and the walking speed fluctuation as a function of the number of passengers present. Moreover, we also conduct the sensitivity analysis under different design conditions and assess the significance of several design parameters.

In order to consider the fluctuation factor, the phase-type (PH) distribution is an appropriate probability distribution that has the ability to fit any positive random number with various CV (c_{a}) and meanwhile keeps the Markovian characteristics [36]. This probability distribution has therefore substituted several other probability distributions, especially the deterministic and exponential distribution. Jiang et al. [37] for the first time used the PH distribution for fitting the passengers' inter-arrival time data at the entrance of an MRT station. The PH distribution has showed opt data fitting effect. The PH distribution takes both the pedestrians' inter-arrival time and CV (c_{a}) of inter-arrival time into consideration. The CV (c_{a}) of the inter-arrival time is the fluctuation factor that depicts the real situation and takes into account the fluctuating demand of pedestrians in MRT stations [38–40], manufacturing production lines [41] and computer and communication systems [42]. The PH distribution has resulted in the emergence of ample PH-based queuing models including PH/PH/1 [43], PH/PH/1/C [44] and PH/PH/K/C [45]. Figure 1 shows the proposed framework of PH-based DES modeling and sensitivity analysis of the passengers' circulation in the transit centers.

3 Passengers' Circulation at the Intermodal Transfer Zone: A Queuing Network Representation

3.1 Notations

The notations used throughout the text are presented below:

Notation	Description
j	Number of the circulation area
λ_{a}^{j}	Passengers' arrival rate to the jth circulation area
$E[T_{\mathrm{a}}]^{j}$	Passengers' inter-arrival time to the jth circulation area
ε	Peak-hour factor
c_{a}^{j}	Coefficient of variation of arrival interval of the jth circulation area
μ_{s}^{j}	Mean service rate of the jth circulation area
$S(n)^{j}$	State-dependence walking speed of passengers in jth circulation area
c_{s}^{j}	Coefficient of variation of service time of the jth facility
Z	Total number of circulation areas in the transfer zone
N^{j}	Capacity of the jth circulation area
Q	Peak-hour volume (ped/h)
h_{m}	Mean headway between the trains
α	Sub-stochastic vector for the passengers' arrival process
D	Sub-generator matrix for the passengers' arrival process
β	Sub-stochastic vector for the service process of the service facility
H	Sub-generator matrix for the service process of the service facility
$E[T]^{j}$	Mean dwell time of passengers in the jth circulation area
$E[A]^{j}$	Mean area occupied per passenger in the jth circulation area
n	Number of passengers in the facility
P_{c}^{j}	Blocking probability in the jth circulation area
f	Degree of Erlang distribution
U	Uniformly distributed random number
θ^{j}	Throughput through jth circulation area

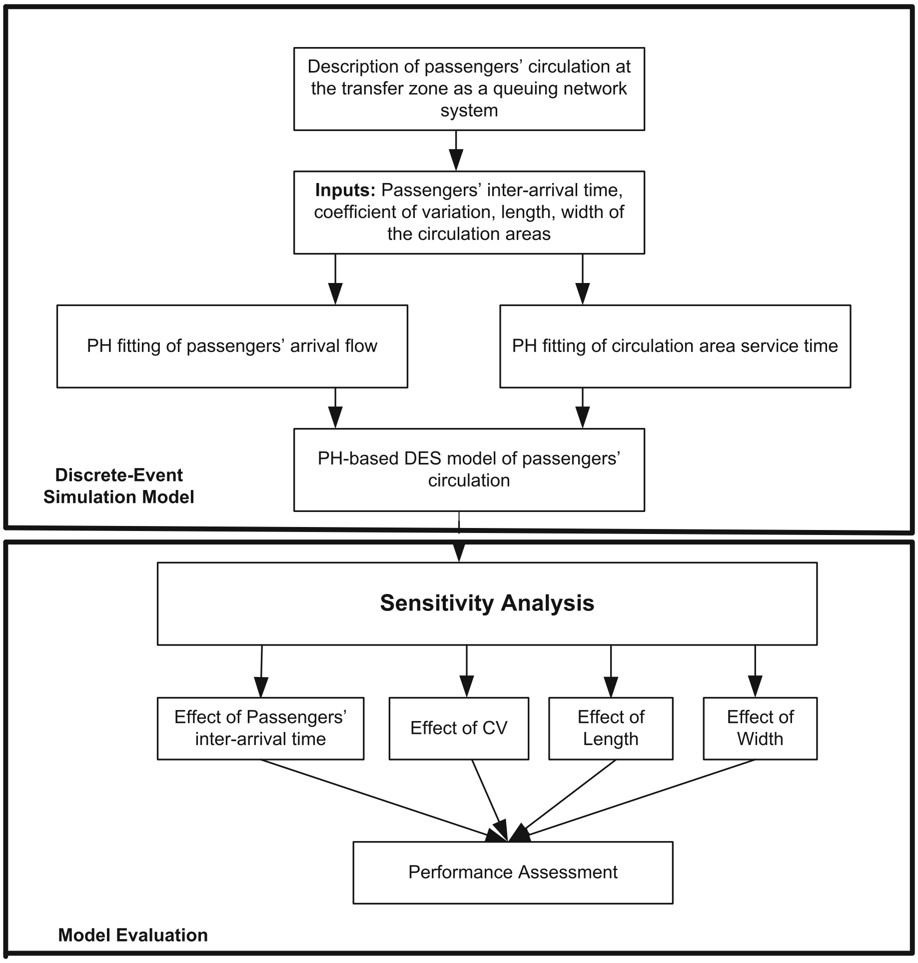

Fig. 1 Proposed framework for the PH-based state-dependent DES modeling and sensitivity analysis

3.2 Mathematical Concept of PH Distribution

The PH distribution is a probability distribution that represents the time to absorption in a continuous-time Markov chain (CTMC) with one absorbing state and all the other transient states [36]. PH distributions are commonly represented by the pair (α, $\mathbf{D}$). Here, α is a sub-stochastic vector, and $\mathbf{D}$ is a sub-matrix depicted as follows:

$$\alpha = (\alpha^1, \ldots, \alpha^m), \mathbf{D} = \begin{pmatrix} d^{11} & \ldots & d^{1m} \\ \vdots & \ddots & \vdots \\ d^{m1} & \ldots & d^{mm} \end{pmatrix}.$$

The probability density function (PDF) and cumulative distribution function (CDF) of PH distribution are given by Eqs. (1) and (2), respectively.

$$f(x) = \alpha(\exp)^{\mathbf{D}x} e \tag{1}$$

$$\boldsymbol{F(x)} = 1 - \alpha(\mathbf{exp})^{\mathbf{D}x} e \tag{2}$$

where

e is a column vector with all elements being one;

α is a sub-stochastic vector of order m, i.e., α is a row vector, all elements of α are nonnegative and$\alpha e < 1$, where m is a positive integer; and

$\mathbf{D}$ is a sub-generator of order m, i.e., $\mathbf{D}$ is an $m \times m$ matrix such that (1) all the diagonal elements are negative; (2) all the off-diagonal elements are nonnegative; (3) all row sums are non-positive.

3.3 Queuing Network of Transfer Zones in the Transit Centers

In this research, we consider a scenario in which a street for the vehicular traffic passes in between different transit centers. The MRT station is on the opposite side of the street to the bus terminal and taxi stop as shown in Fig. 2. They are connected by a network of transfer zones (stairways and elevated passageways). It should be noted that we consider only the unidirectional flow of passengers heading toward bus terminal and taxi stop from the MRT station. Neverthe-

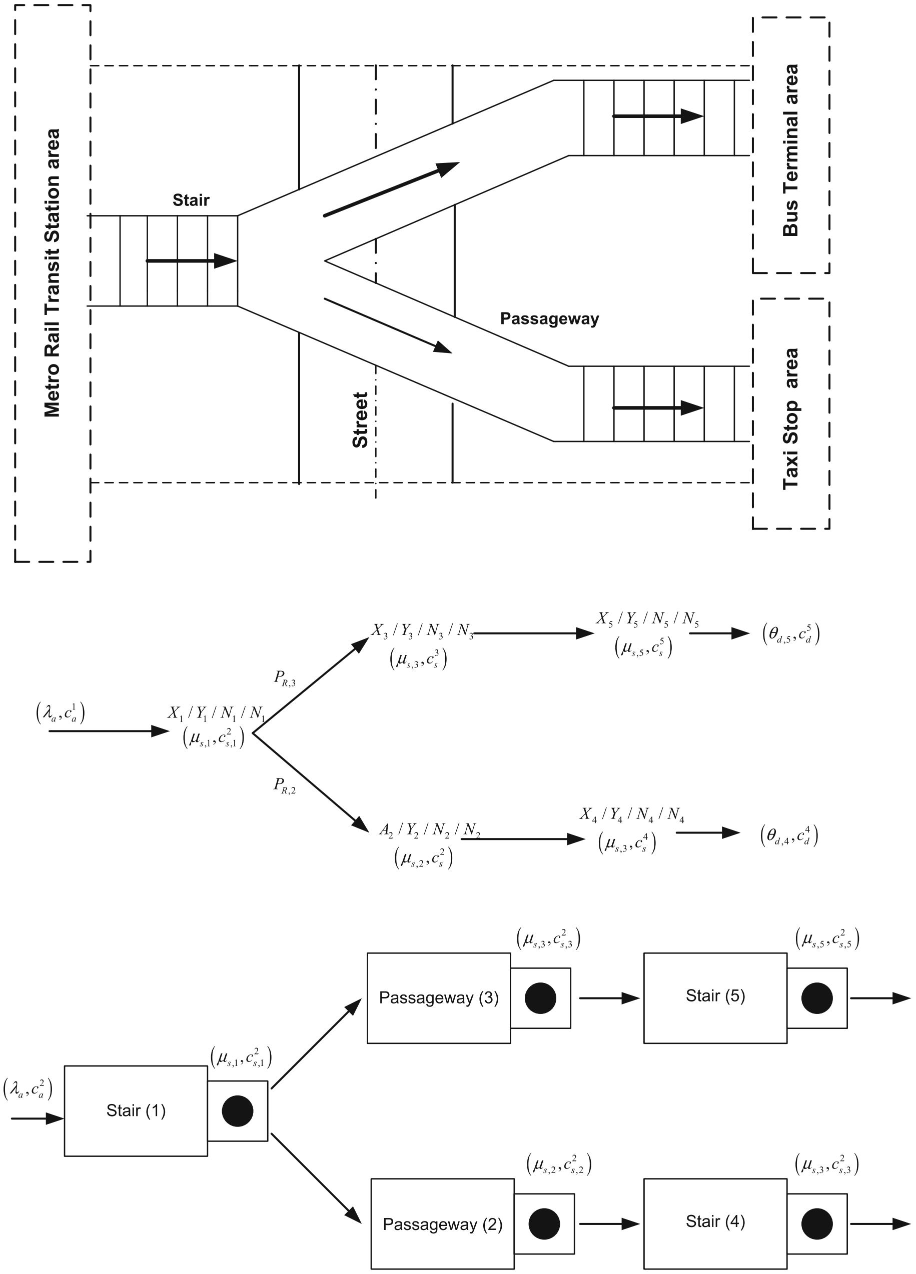

Fig. 2 Queuing network representation of the passengers' transfer zone

less, bidirectional flow can also be considered by taking the weighted mean of passengers' flow in both directions. In case of unidirectional flow, the passengers at the egress of the MRT station use the upstream (ascending) stairs and the elevated passageways to cross the street and ingress the bus terminal and taxi stop via two downstream descending stairs. From Fig. 2, it is clear that passengers' circulation at the intermodal transfer zone can be transformed into a topology of a queuing network system in which the passengers enter the transfer zone at ascending stairs (egress MRT station), spend some time while traversing the transfer zone (receiving services) and finally leave via descending stairs. Each transfer zone is a node ($j = 1, 2 \ldots, Z$) of a queuing network and described as $X^j/Y^j(n)/N^j/N^j (j = 1, 2 \ldots, Z)$ queuing system, where Z is the total number of transfer zones in a queuing network system.

The passengers' arrival flow to any jth node in the queuing network system of intermodal transfer facility is indicated by the mean passengers' inter-arrival time $E[T_\mathrm{a}]^j = 1/\lambda_\mathrm{a}^j$ and the CV (c_a^j) [28], where λ_a^j is the mean passengers' arrival rate to the jth node in the queuing network system. In order to obtain the passengers' arrival flow indicators, the peak-hour passengers' volume (Q), peak-hour factor (ε), mean headway (h_m) between trains and CV in the successive trains' headway (c_h) are required to be predetermined from the field survey data. The mean passengers' inter-

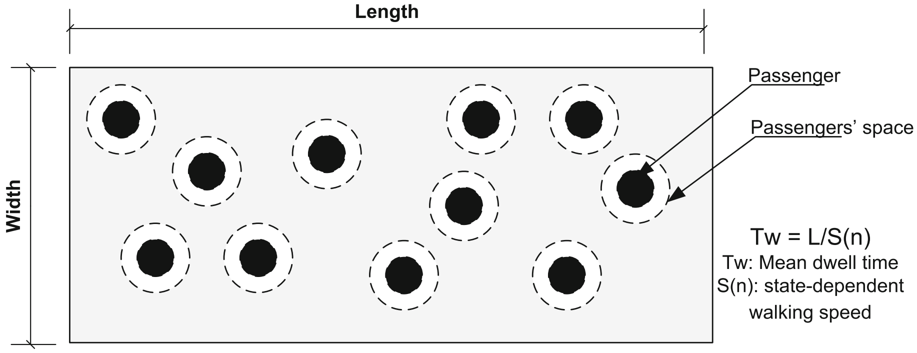

Fig. 3 Passengers' spaces in a rectangular transfer area

arrival time $E[X_{\mathrm{a}}]^j = 1/\lambda_{\mathrm{a}}^j$ can be obtained by using Eq. (3):

$$E[T_{\mathrm{a}}]^j = 1/\lambda_{\mathrm{a}}^j = \frac{3600\varepsilon}{Q} \quad (\mathrm{s}) \tag{3}$$

The value of CV (c_{a}^i) of inter-arrival time can be calculated from Eqs. (4) and (5):

$$c_{\mathrm{a}}^j = \sqrt{\frac{\exp^{6.819\varepsilon}(\varepsilon-1)^2}{4\varepsilon-1}} \tag{4}$$

$$c_{\mathrm{a}}^j = \sqrt{\exp^{0.503c_h^2}\left[\left(\frac{Qh_m}{3600\varepsilon}\right)-1\right]} \tag{5}$$

For simplicity, the passengers' transfer zone is assumed to be a rectangular having length (*L*) and width (*W*). However, different zigzag-shaped transfer zones can be analyzed by converting them into a rectangular shape. In each transfer zone, passengers occupy the spaces as they enter. Each passenger's space in the transfer zone acts as single server. If density of passengers in each rectangular transfer zone is known, the capacity can be calculated by using Eq. (6).

$$N^j = k^j L^j W^j \tag{6}$$

The passengers spend a certain amount of time traversing the transfer zone. The time associated with the movement of passengers in the transfer zone is known as the passengers' walking time or dwell time 'T_{d}.' Therefore, the passengers' circulation in the intermodal transfer zone is a kind of multi-server, finite-capacity queuing system with the passengers as entities, the passengers' spaces as servers and the traversing or dwell time during circulation as a service time.

It should be noted that the number of available spaces reduces as the number of passengers 'n' increases in the transfer zone. Practically, the number of passengers 'n' changes in the passengers' transfer zone dynamically over the time. When the increasing number of passengers 'n' in the transfer zone increases, the density 'k' of the passengers increases and ultimately reduces the passengers' walking speed 'S' as shown in Fig. 3. Thus, the phenomenon of disparity in the passengers' walking speed with the presence of surrounding passengers is known as the state-dependence walking speed '$S(n)$' and the mean dwell time becomes state-dependent dwell time $T_d(n)$. The state-dependent passengers' walking speed $S(n)$ reduces to zero and the movement of passengers halts when the number of passengers 'n' approaches the capacity of transfer zone.

Therefore, any jth passengers' transfer zone can be represented as a finite-capacity, multi-server, state-dependent queuing system with the passengers' inter-arrival time described by X^j and state-dependent service time of the passengers' transfer zone by $Y^j(n)$. The number of available positions in the passengers' transfer zones is viewed as the servers and represented by N^j, while the capacity of transfer zones, which is also equal to the number of servers, is represented by $N^j = k^j L^j W^j$. Therefore, the general form to represent any jth passengers' transfer zone is $X^j/Y^j(n)/N^j/N^j$ queuing system.

Furthermore, in order to simplify the analysis of passengers' transfer zones, the finite-capacity, multi-server state-dependent queuing system ($X^j/Y^j(n)/N^j/N^j$) is transformed into a finite-capacity, single-server, state-dependent queuing system ($X^j/Y^j(n)/\mathbf{1}/N^j$). The idea is supported by Hu et al. [4] and Khattak et al. [5] who demonstrated that the ($X^j/Y^j(n)/N^j/N^j$) state-dependent queuing model with a single server is equivalent to the ($X^j/Y^j(n)/\mathbf{1}/N^j$) queuing model. The transformation proceeds as follows:

- A virtual line and a virtual server are positioned at the exit of the jth passengers' transfer zone, as shown in Fig. 4. A virtual server serves one (single) passenger at a time, which is analogous to the single passenger passing through the virtual line.
- When two sequential passengers pass through the virtual line, the inter-arrival time (dwell time) 'T_{d}^j' between them is recorded.
- If the time at which the previous passenger leaves the virtual server is viewed as the time the next passenger begins to be served, then the time interval between these

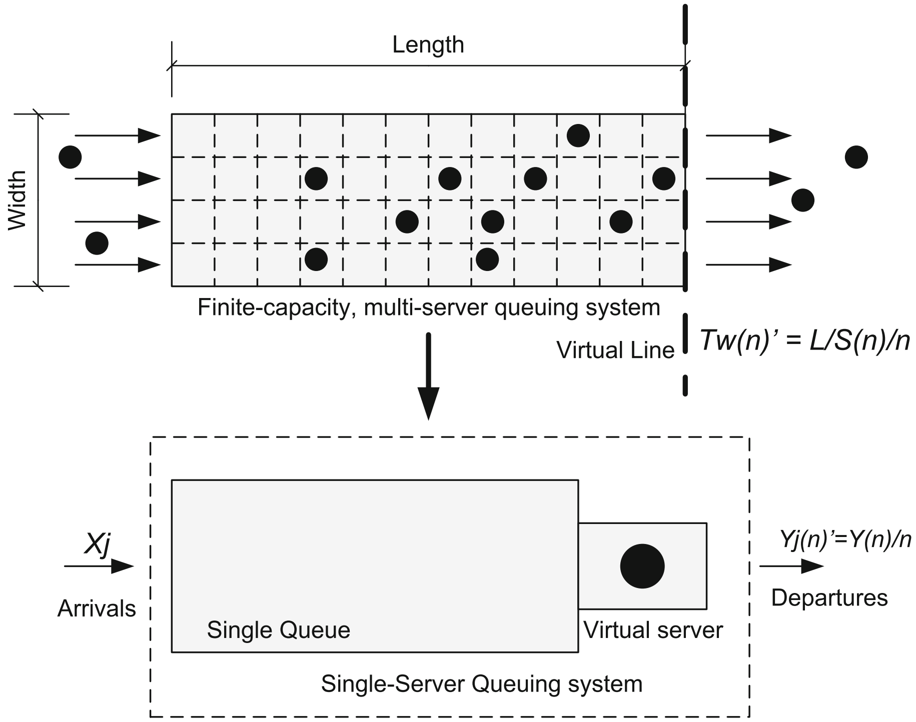

Fig. 4 Transformation of passengers' transfer zone to a single-server queuing system

two sequential passengers passing through the virtual line is equal to the service time of the virtual server.

- In this way, the multi-server $(X^j/Y^j(n)/N^j/N^j)$ queuing system with N^j servers can be transformed equivalently into a single-server $(X^j/Y^j(n)'/\mathbf{1}/N^j)$ queuing system.
- It should also be noted that the service time of the single server becomes $Y_i'(n) = Y_i(n)/n$, which is the function of the number of passengers 'n.'

The TCRP-Report 165 describes the service rate (μ) of any facility as Eq. (7):

$$\mu = kS \tag{7}$$

The service rate is reciprocal to the service time of any facility, and therefore, the dwell time of passengers in the transfer zone (T_{d}) is actually the service time of transfer zone (T_{s}). In case of state dependence, the service time of any jth transfer zone can also be expressed as Eq. (8):

$$T_{\text{s}}^j(n) = 1/\mu(n)^j = L^j/nS(n)^j \quad (j = 1, 2 \ldots, Z) \tag{8}$$

We substitute the term $S(n)^j$ in Eq. (8) with the exponential-based state-dependent passengers' walking speed expression developed by Yuhaski and Smith [46] to determine the state-dependent service time of passengers' transfer zone. The expression for exponential-based passengers' walking speed is shown in Eq. (9).

$$S(n)^j = S_1 \exp\left[-\left(\frac{n-1}{\upsilon^j}\right)\right]^{\zeta^j} \quad (j = 1, 2 \ldots, Z) \tag{9}$$

where

$$\zeta_j = \left[\frac{\ln\left(\frac{S_{j,A}}{S_{j,1}}\right)}{\ln\left(\frac{S_{j,A}}{S_{j,1}}\right)} - \ln\left(\frac{A_j - 1}{B_j - 1}\right)\right]$$

$$\upsilon_j = (A_j - 1)\left[\ln\left(\frac{S_{j,1}}{S_{j,A}}\right)\right]^{1/\zeta_j}$$

By substitution, we obtain

$$T_{\text{s}}^j(n) = L^j/nS_1 \exp\left[-\left(\frac{n-1}{\upsilon^j}\right)\right]^{\zeta^j} \quad (j = 1, 2 \ldots, Z) \tag{10}$$

Similarly, Hu et al. [4] developed an analytical expression for CV $(c(n)_{\text{s}}^j)$ of service time for any jth transfer zone shown in Eq. (11).

$$c(n)_{\text{s}}^j = \frac{\delta_1^j}{S_1^j} \exp\left(\left(\frac{n-1}{\upsilon^j}\right)^{\zeta^j} - \left(\frac{n-1}{\upsilon'^j}\right)^{\zeta'^j}\right) \tag{11}$$

where

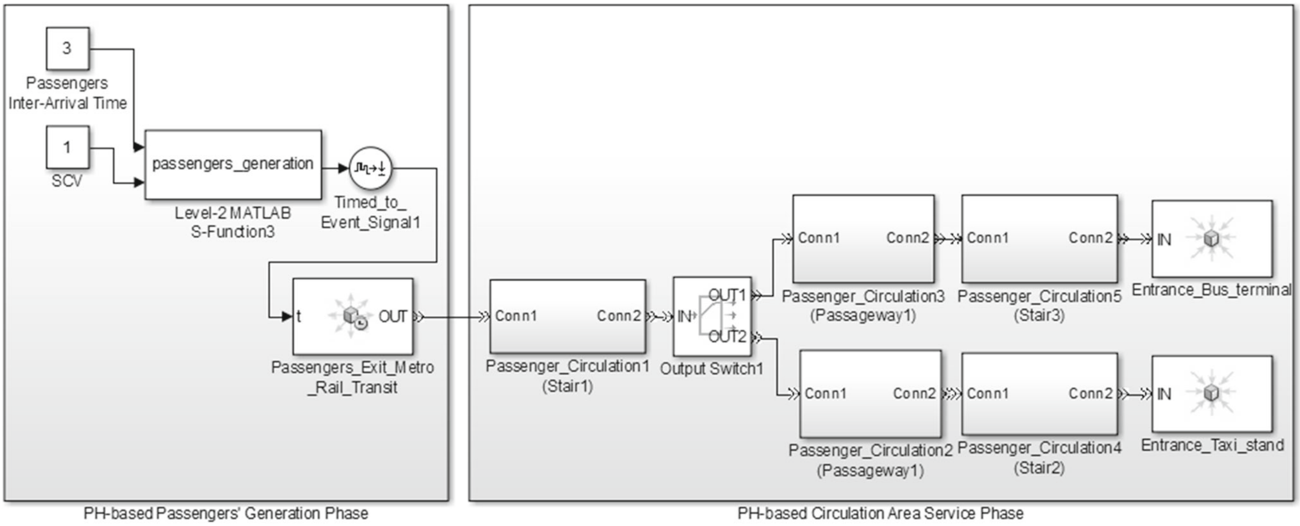

Fig. 5 *SimEvents*® implementation of the passengers' circulation at the transfer zone

$$\upsilon'^{j} = \left[\frac{\ln\left(\frac{\delta_A^j}{\delta_1^j}\right)}{\ln\left(\frac{\delta_A^j}{\delta_1^j}\right)} - \ln\left(\frac{A^j - 1}{B^j - 1}\right)\right]$$

$$\zeta'^{j} = (A^j - 1)\left[\ln\left(\frac{\delta_A^j}{\delta_B^j}\right)\right]^{1/\gamma^j}$$

(v_1^j, δ_1^j)	Mean and standard deviation of the passengers' walking speed when there is a single passenger in the jth passengers' transfer zone
(v_A^j, δ_A^j)	Mean and standard deviation of passengers' walking speed when $A^j = 2L^j W^j$ passengers occupy the jth passengers' transfer zone
(v_B^j, δ_B^j)	Mean and standard deviation of passengers' walking speed when $B^j = 4L^j W^j$ passengers occupy jth passengers' transfer zone.

4 State-Dependent DES Model Architecture of Passengers' Circulation

A PH-based state-dependent DES model of passengers' circulation in the intermodal transfer zone is developed in the *SimEvents*® software module. Each jth passenger's circulation (stairways and passageways) is described as a queuing system based on the PH distribution, i.e., the $\mathrm{PH}^j/\mathrm{PH}^j(n)/N^j/N^j$ queuing model, and represented by a *subsystem* block as shown in Fig. 5.

The major components of the *SimEvents*® module (shown in detail by Fig. 6) involved in the development of the PH-based state-dependent DES model are the *FIFO_Queue* blocks that store the passengers' queue, the *single-server* block that stores the passengers for a certain period of time associated with the movement in the transfer zone, the *Start and Read Timer* blocks that report the dwell time of passengers in the transfer zone, the *MATLAB*® function blocks that compute various performance measure values, the *Level-2 S-function* block which computes the PH-distributed random variates as well as dynamically updates the service time as a function of number of passengers present. *Constant* blocks are used to enter various design parameter values in the DES model. The*Display* blocks report the performance measure values. The whole PH-based state-dependent DES model is divided into two stages, i.e., passengers' arrival stage based on the PH-distributed random numbers and passengers' circulation state-dependent service stage based on PH-distributed random variates. Therefore, before the initiation of these stages, it is required to generate PH-distributed random variates.

4.1 PH-Distributed Random Variates Generation

As discussed earlier, the PH distribution is used in this research for fitting the passengers' inter-arrival time as well as state-dependent service time of the passengers' transfer zone. The first key ingredient of the PH-based state-dependent DES model is the generation of PH-distributed random variates by using the sub-stochastic vector and sub-generator matrix. Neuts [36] has developed a 'Count technique' for the generation of PH-distributed random variates. This technique involves generating an Erlang-distributed sample with a degree (f), parameter (σ) and uniformly distributed random number $U \sim [0, 1]$. Drawing an Erlang-distributed sample of length f_j requires a single

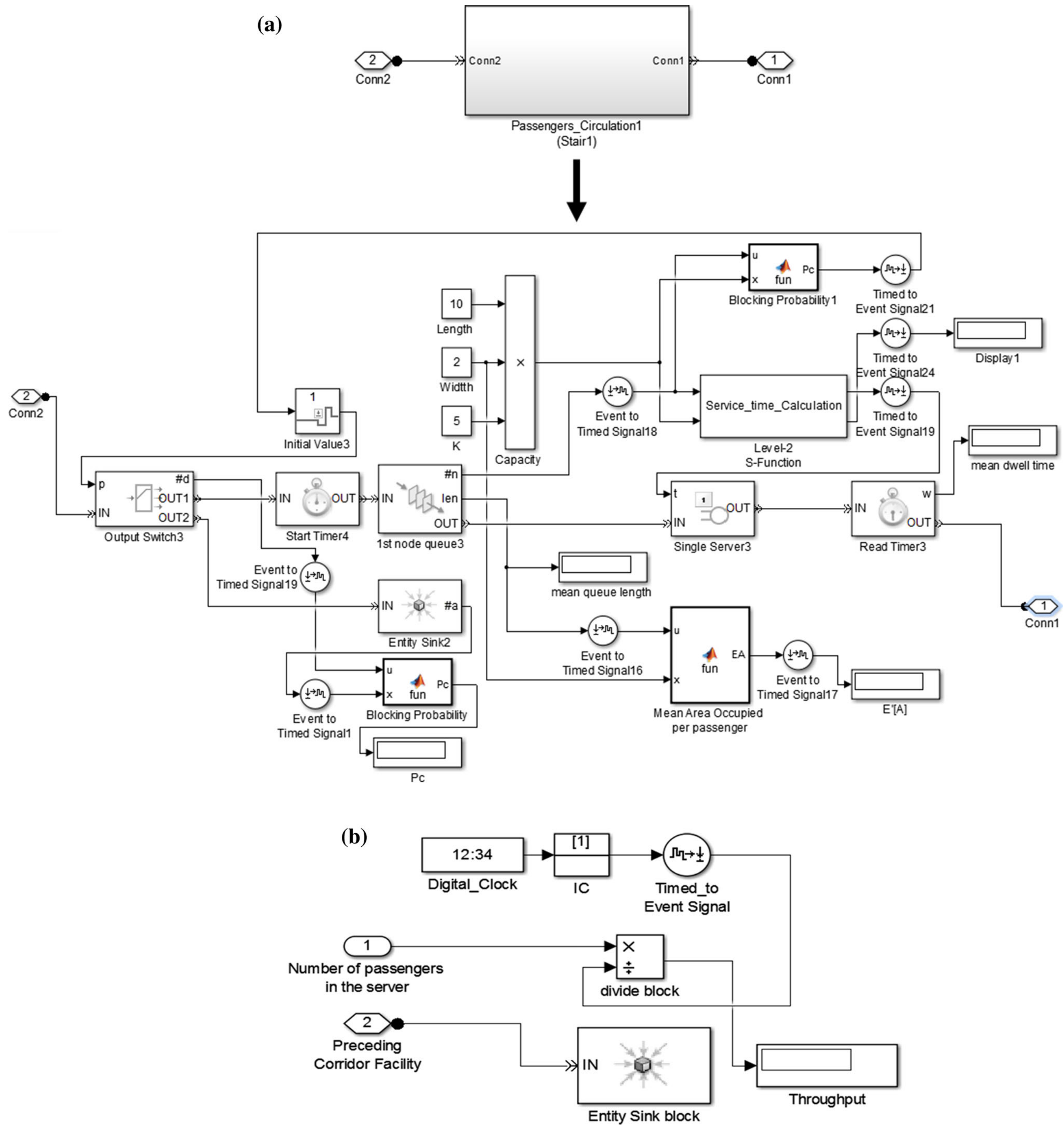

Fig. 6 PH-based state-dependent service stage at each subsystem. **a** PH-based state-dependent service stage, **b** termination stage

step computation of a logarithmic function. It counts the amount of visits and then draws a single Erlang-distributed sample for each state.

$$\mathrm{Erl}(f, \sigma) = -\frac{1}{\sigma} \ln \left(\prod_{j=1}^{f} U_j \right)$$

A row vector that has a value of 1 at position r is represented by v^r. Selecting the initial or successor state involves drawing an additional random number from the 'U.' The pseudo-codes description of PH-distributed random variates generation is given in Table 1.

Table 1 Pseudo-code for PH-distributed random variates

```
Initial State:
    $\chi^{\mathrm{PH}} := 0$
    $f_r = 0\,(r = 1, 2......n)$
    An $\alpha$-distributed sample for the initial state.
At State 'r'
    When the chain in the state 'r'
    $f_j += 1$
    a $\boldsymbol{v}^{j}(\text{-}\mathbf{diag}\langle \mathbf{1/d}^{rr}, \mathbf{0}\rangle \overline{\mathbf{D}} + \mathbf{I})$-distributed sample is drawn for the next state,
    If next state is an absorbing state
        $\chi^{PH} += Erl(f_r, \text{-}d_{rr})\,(r=1, 2....n)$
    Else
        Repeat drawing $\boldsymbol{v}^{r}(\text{-}\mathbf{diag}\langle \mathbf{1/d}^{rr}, \mathbf{0}\rangle \overline{\mathbf{D}} + \mathbf{I})$-distributed sample.
    End
Return
    $\chi^{PH}$
```

4.2 PH-Based Passengers' Arrival Stage

In the PH-based passengers' arrival stage as shown in Fig. 5, the passengers are first produced at the stairway ($j = 1$), the egress of the MRT station heading toward the bus terminal or taxi stop. The two-input passengers' arrival flow descriptors for the generation of PH-distributed random variates are the passengers' inter-arrival time and CV (c_{a}^{1}) (Khattak et al. [5]) and can be obtained by Eqs. 3 and 4, respectively. Previously, Hu et al. [4] attained opt fitting effect for the passengers' inter-arrival time at the entrance and exit of MRT stations and for the state-dependent service time of corridor facility in the MRT stations by using PH distribution. The required inputs for fitting the PH distribution to the arrivals of passengers are λ_{a}^{j} and $\mathrm{CV}(c_{\mathrm{a}}^{j})$, but there are certain conditions that are given in Table 2 (Sadre [47]; Sadre and Haverkort [48]).

Based on Table 1, the passengers' arrival process (X^{j}) can be described by the sub-stochastic vector (α^{j}) and sub-generator matrix ($\mathbf{D}^{j}$) as:

$$X^{j} \sim \mathbf{PH}(\alpha^{j}, \mathbf{D}^{j}) \quad (j = 1, 2 \ldots, Z)$$

4.3 PH-Based State-Dependent Service Stage

Each passenger' circulation in the queuing network model has a finite capacity. It is necessary that passengers' arrival demand (number of passengers) should not overcome the overall capacity of passengers' transfer zone. After the production of passengers in the first stage, it must be assured that the number of arrivals remains less than or equal to $N^{j} = k^{j} L^{j} W^{j}$.

To execute this situation for any jth passengers' transfer zone in the *SimEvents*® software module, the passenger arrivals from the $(j - 1)$th transfer zone accumulate in the *FIFO_Queue* block prior to entering the *Single_Server* block. The passengers are subsequently sent to the $(j + 1)$th successor passengers' transfer zone.

Table 2 Condition for the phase-type (PH) distribution

Distribution	CV	α	$\mathbf{D}$
Hypo-exponential	< 1	$\alpha = (1, 0, \ldots, 0)$	$\mathbf{D} = \begin{pmatrix} -d^{0} & d^{0} & & & \\ & -d^{1} & d^{1} & & \\ & & .. & .. & \\ & & & -d^{m-2} & d^{m-2} \\ & & & & -d^{m-1} \end{pmatrix}$
Hyper-exponential	> 1	$\alpha = (g, 1 - g)$	$\mathbf{D} = \begin{pmatrix} \frac{-2g}{E[X]} & 0 \\ 0 & \frac{-2(1-g)}{E[X]} \end{pmatrix}$
Exponential	$= 1$	1	$-d$
Deterministic	$\leq 1/30$	*Equivalent to the Erlang-30 distribution*	

- $m = \frac{1}{CV}$
- $d^{r} = \frac{m}{E[T_{\mathrm{a}}]}$ for $0 \leq r < m - 2$
- $d^{m-1} = \frac{2m[1+\sqrt{\frac{1}{2}m(mCV-1)}]}{E[T_{\mathrm{a}}](m+2-m^{2}CV)}$
- $d^{m-2} = \frac{m\lambda^{m-1}}{(2\lambda^{m-1}E[T_{\mathrm{a}}]-m)}$
- $g = \frac{1}{2}[1 + \sqrt{\frac{CV-1}{CV+1}}]$

The *MATLAB*® *Function* blocks are used to perform the following tasks:

- It computes the mean area occupied per passenger $(E[A]^j)$ in the jth passengers' transfer zone. It is calculated by using the area of the jth transfer zone $(A^j = L^j W^j)$ divided by the mean queue length $(E[N]^j)$ directly reported by the *FIFO_Queue* block.
- It compares the number of passenger arrivals (n^j) to the jth passengers' transfer zone with the capacity $(N^j = k^j L^j W^j)$ of the jth passengers' transfer zone and prevent them from entry when the maximum capacity $n^j = N^j$ is reached.
- It computes the blocking probability (P_c^j) in the jth passengers' transfer zone. When the capacity $(N^j = k^j L^j W^j)$ reaches the maximum of the jth passengers' transfer zone, i.e., $n^j = N^j$, the passengers are blocked to enter the *FIFO_Queue* block. At the same time, the 2nd entity port (OUT2) of *Output Switch* block activates and registers the blocked passengers. The blocking probability (P_c^j) is the ratio of the number of passengers who left via the 2nd entity port of the *Output Switch* block to the total number of passengers left via both the 1st (OUT 1) and 2nd ports (OUT 2).

The *Level-2 S-function* blocks are used in this stage to compute and dynamically update the state-dependent service as a function of the number of passengers present. The state-dependent service time of any jth passengers' transfer zone $(T_s^j(n))$ calculation depends on the congestion in the transfer zone. The *Level-2 S-function* block (renamed as state-dependent service time) as shown in Fig. 6 uses the capacity of the jth passengers' transfer zone $(N^j = k^j L^j W^j)$ and the number of passengers (n^j) from the *FIFO_Queue* block as the two inputs to compute the state-dependent service time of the jth passengers' transfer zone $(T_w^j(n))$ and $\mathrm{CV}(c(n)_s^j)$. Equations (10) and (11) are programmed in the *Level-2 S-function* block.

Similar to the arrival stage, the state-dependent service stage $(Y^j(n))$ of the jth passengers' transfer zone can be described by sub-stochastic vector $(\beta^j(n))$ and sub-generator matrix $\mathbf{H}^j(\boldsymbol{n})$ using $(T_s^j(n))$, $\mathrm{CV}(c_s^j(n))$ and with the help of Table 1 as:

$$Y^j(n) \sim \mathbf{PH}[\beta^j(n), \mathbf{H}^j(n)]$$
$$(j = 1, 2 \ldots, Z)(n = 1, 2 \ldots, N)$$

It should be noted that the activities in the state-dependent service stage are executed in a similar manner in all transfer zones. The difference in stairways and passageways performance measure may arise due to the differences in the passengers' walking speeds. The slower movement of passengers on the stairways may cause congestion issues if the size of the stairways is inadequate.

5 Computational Experiments

The computational experiments section consists of three subsections that include the data description and comparison of the selected probability distributions, verification of the PH-based state-dependent DES model and sensitivity analysis under various design parameters.

5.1 Data Description and Comparison of Selected Probability Distributions

The passengers' arrival flow data are obtained first from the field survey of major transit centers in Beijing and Chengdu. The Beijing Chongwenmen station is a transfer station of Line # 1 and Line # 5, Chengdu Tianfu Square station is the transfer station of Line # 1 and Line # 2, and the Chengdu North Metro station is the transfer station of Line # 1 and North Railway Station. The data were collected during the morning peak (07:30 am to 08:30 am), flat peak (11:30 am to 12:30 pm) and evening peaks (17:30 pm to 18:30 pm). We then examined inter-arrival time distribution of collected data and fitted probability distributions to the observed data set. As mentioned previously, the passengers' arrival process generally assumed to follow exponential, uniform and gamma distributions. Thus, we have fitted the observed data set with these distributions. In addition, we have also selected three other distributions, namely normal, Weibull and log-normal distributions, because of their high performance. The resulting PDFs of six distributions are shown in Fig. 7. It should be noted that the PDF of uniform distribution is not shown in Fig. 7 because its PDF is a horizontal line, which is considerably different from other PDFs.

Moreover, the coefficient of determination (R^2) of the probability function is used in this study to evaluate the fitting quality of the selected probability distributions. The results indicate that the PH distribution performs the best in terms of fitting quality which is followed by gamma and Weibull distributions. Therefore, the PH distribution is the best choice to be used to describe inter-arrival time of passengers at service facilities in the transit centers.

5.2 Verification of the PH-Based State-Dependent DES Model

Before carrying out the sensitivity analysis of the passengers' transfer zone by using PH-based state-dependent DES model, it is necessary to validate the accuracy of proposed PH-based state-dependent DES model. For this purpose, the simulation tests were conducted, and results were com-

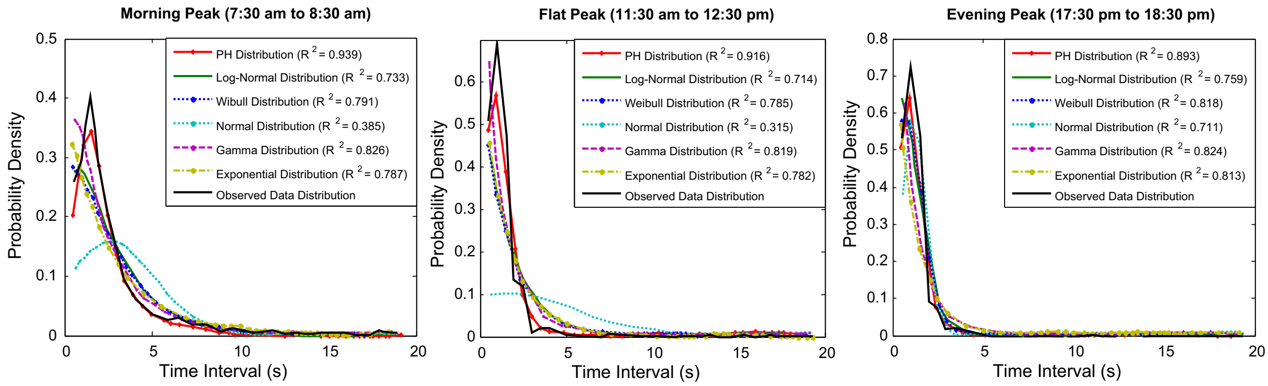

Fig. 7 Comparison of different probability distributions

pared with the PH-based analytical models. There are two ways to assess our PH-based state-dependent DES for its accuracy.

- One way is to transform the PH-based state-dependent DES model into the exponential-based($M/G(n)/N/N$) DES model by setting the values of $\mathrm{CV}(c_\mathrm{a}^1)$ and $\mathrm{CV}(c_\mathrm{s}^j)$ equal to 1(as discussed earlier in Table 2) and compare the results with an existing exponential-based model (Cruz et al. [13]).
- Another way is to compare the PH-based state-dependent DES model with an existing PH-based analytical model (Zhu et al. [6])

For validation, a simple queuing network model is developed that consists of three passageways in series, splitting and merging topologies with sizes $15 \times 4\,\mathrm{m}^2$, $30 \times 2\,\mathrm{m}^2$ and $15 \times 4\,\mathrm{m}^2$. Tests were performed with different passengers' arrival rate (λ_a^1) and $\mathrm{CV}(c_\mathrm{a}^1)$. The results were obtained after 30 replications each with a simulation time of 200,000 units. The higher simulation time unit was set to achieve the steady-state condition, and performance measure values were noted at the end of simulation. The mean computational times (CPU times in minutes) were also recorded for all experiments. Moreover, the 95% confidence interval approximations, if sampling distribution of the mean follows normal distribution, are also obtained and recorded. The performance measures that include the blocking probability P_c, mean dwell time (E[T]), throughput θ and mean area per passenger (E[A]) were obtained by both PH-based analytical and PH-based state-dependent DES model and are presented in Table 3. From Tables 3 and 4, the PH-based state-dependent DES model has achieved clear consistency with the PH-based analytical method and exponential-based $(M/G(n)/N/N)$ DES model by setting the values of $\mathrm{CV}(c_\mathrm{a}^1)$ and $\mathrm{CV}(c_\mathrm{s}^j)$ equal to 1. Therefore, PH-based state-dependent DES model can be used for the sensitivity analysis of the passengers' transfer zone.

5.3 Sensitivity Analysis

In case of passengers' circulation at an intermodal transfer zone, it is important to study how the variation in the values of certain design parameters affects the performance of passengers' transfer zones or the values of some other parameters. Several questions arise while looking at the passengers' circulation network in Fig. 2. Some of the questions are: On an average, how much is the dwell time of each passenger while traversing the passengers' transfer area network?

Table 3 Comparison of PH-based state-dependent DES model with PH-based analytical model

Inputs		Models	Performance measures				
λ_a^1	$\mathrm{CV}(c_\mathrm{a}^1)$		θ	$E[T]$	$E[A]$	P_c	Mean CPU time (min)
1.65	100	PH-based DES	1.69 (1.61, 1.76)	52.45 (52.32,52.52)	2.27 (2.19, 2.34)	0.00 (0.00, 0.00)	18.53
		PH-based analytical	1.66	49.93	2.33	0.00	
1.75	100	PH-based DES	1.82 (1.74, 1.89)	56.23 (56.15, 56.30)	2.25 (2.17, 2.32)	0.00 (0.00, 0.00)	20.41
		PH-based analytical	1.77	52.11	2.18	0.00	
1.95	100	PH-based DES	2.03 (1.95,2.10)	68.89 (68.81, 68.96)	1.95 (1.87, 2.02)	0.00 (0.00, 0.00)	20.85
		PH-based analytical	1.95	65.17	1.91	0.00	

Table 4 Comparison of PH-based state-dependent DES and the exponential-based ($M/G(n)/N/N$) DES model

	Passageway 1		Passageway 2		Passageway 3		CPU time (min)
	$M/G(n)/N/N$	PH-based DES $c_a^1 = 1, c_s^j = 1$	$M/G(n)/N/N$	PH-based DES $c_a^1 = 1, c_s^j = 1$	$M/G(n)/N/N$	PH-based DES $c_a^1 = 1, c_s^j = 1$	
	Series topology						2.26
P_c	0.33	0.32 (0.24, 0.39)	0.00	0.00 (0.00, 0.00)	0.00	0.00 (0.00, 0.00)	
θ	2.01	2.00 (1.92, 2.07)	2.01	2.00 (1.91, 2.05)	2.01	2.01 (1.94, 2.09)	
$E[T]$	48.31	47.95 (47.87, 48.02)	7.26	8.10 (8.02, 8.17)	7.26	8.02 (7.94, 8.08)	
	Merging topology						3.20
P_c	0.33	0.32 (0.24, 0.39)	0.33	0.32 (0.24, 0.39)	0.53	0.52 (0.45,0.59)	
θ	2.00	1.98 (1.90, 2.04)	2.00	1.98 (1.89, 2.04)	2.00	1.99 (1.92, 2.06)	
$E[T]$	47.82	47.61 (47.50, 47.72)	47.82	47.33 (47.27, 47.41)	50.54	50.11 (50.02, 50.21)	
	Splitting topology						2.42
P_c	0.33	0.32 (0.24, 0.39)	0.00	0.00 (0.00, 0.00)	0.00	0.00 (0.00, 0.00)	
θ	2.01	2.00 (1.93, 2.07)	1.04	1.04 (0.97, 1.11)	1.04	1.04 (0.97, 1.11)	
$E[T]$	48.31	47.95 (47.92, 47.82)	7.53	7.45 (7.38, 7.52)	7.53	7.45 (7.38, 7.52)	

How many passengers are in the system? Could changes in the passengers' inter-arrival time and CV affect the blocking probability of passengers or other performance measures? As discussed earlier, the PH-based state-dependent DES model with CV(c_a^i) equal to 1 is analogous to the exponential-based $M/G(n)/N/N$ model (Cruz et al. [25]), while CV(c_a^i) equal to 1/30 is analogous to the TCRP-Report 165 ($D/D(n)/C/C$ model).

For the sensitivity analysis, 36 groups of PH-based state-dependent DES tests were performed with $\lambda_a^i = 2500$ ped/h and $\lambda_a^i = 3600$ ped/h with different values of CV(c_a^i), i.e., 1/30, 1, 50 and 100.

Experiments were performed on four differently sized passenger circulations in the form of a network. The different sizes of passenger circulation under investigation were $10 \times 2\,\mathrm{m}^2$, $10 \times 3\,\mathrm{m}^2$, $20 \times 2\,\mathrm{m}^2$ and $20 \times 3\,\mathrm{m}^2$. It should be noted that each experiment, the sizes of stairs and passageways were kept the same. The passengers' walking speed parameters in the passageways were ($\nu_1^j = 1.50$, $\delta_1^j = 0.50$), ($\nu_A^j = 0.32$, $\delta_A^j = 0.21$) and ($\nu_B^j = 0.25$, $\delta_B^j = 0.8$), respectively, while the passengers' walking speed parameters in the stairs were ($\nu_1^j = 0.75$, $\delta_1^j = 0.25$) ($\nu_A^j = 0.16$, $\delta_A^j = 0.11$) and ($\nu_B^j = 0.12$, $\delta_B^j = 0.04$), respectively.

The passengers' arrival rate (λ_a^1) can also be calculated by using Eq. 3, if the peak-hour volume, peak-hour factor and headway between the trains are known. Similarly, the values of CV(c_a^i) can be calculated according to Eqs. 4 and 5. All the computational experiments are carried out on a PC with 3.2 GHz of Intel Core i5-4700 365 CPU and 8 GB of RAM under a Windows 8 operating system.

The issue explored in this section is the effects of passengers' arrival rate (inter-arrival time) 6(λ_a^1) ($1/E[X_a]$), the CV(c_a^1) of the inter-arrival time, and sizes (length L and width W) of the transfer zone on the mean number of passengers (mean queue length) ($E[N]$), blocking probability (P_c), mean dwell time ($E[T]$) and the mean area occupied per passenger ($E[A]$). It is observed that an increasing passengers' arrival rate (λ_a^1) would lead to an increase in the mean number of passengers ($E[N]$) (see Fig. 8) and mean dwell time of passengers in the passengers' transfer zone ($E[T]$). One could be interested in finding the effect of the CV(c_a^1) of inter-arrival time on the performance measures while keeping the passengers' arrival rate (λ_a^1) constant.

The performance measures indicate that as CV (c_a^1) increases, the mean number of passengers ($E[N]$) and mean dwell time of passengers increase ($E[T]$), while the mean area per passengers drops ($E[A]$) for all the sizes of transfer zone. The upstream stair (ascending stair) ($j = 1$) experiences heavy passengers' traffic at the egress of the MRT station. The passengers' blocking (P_c) occurs when CV (c_a^1) increases due to uncertainty (irregularity) in the passengers'

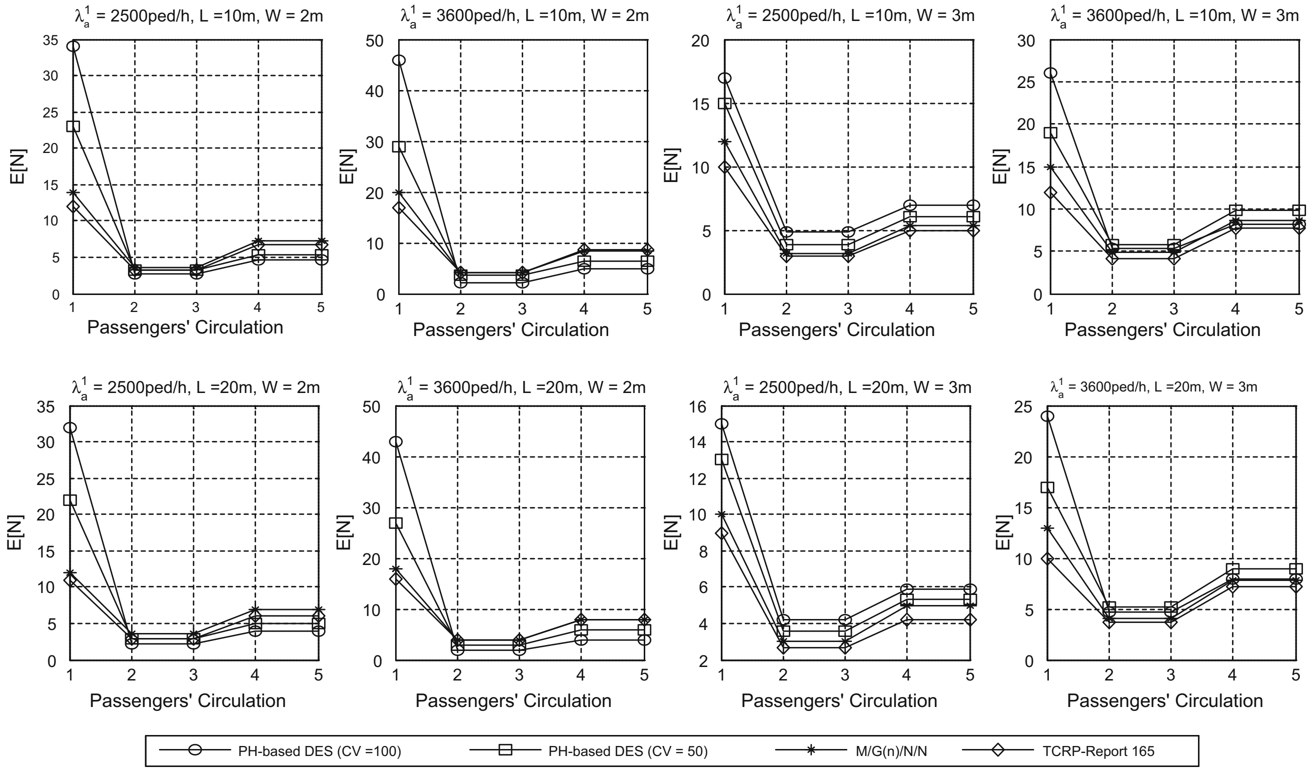

Fig. 8 Mean number of passengers in the transfer zone under different λ_a^1, CV(c_a^1), length and width

flow at different instants. In case of CV (c_a^1) equal to 1 ($M/G(n)/N/N$) and 1/30 (TCRP-Report 165), the blocking probability is zero, which means that irregular and random arrivals are ignored which does not depict the actual scenario. It has been observed that doubling the length ($L = 10$ m to $L = 20$ m) for both the lower and higher passengers' arrival rate has no major impact on the performance measure values, while major changes have been observed when the width is increased from $W = 2$ m to $W = 3$ m.

Figure 9 shows the graph of blocking probabilities (P_c) measures against the passenger' circulation for all the passengers' arrival rates (λ_a^1), CV (c_a^1) of inter-arrival time and sizes of transfer areas. The blocking occurs at the upstream (ascending) stair ($j = 1$) at the higher passengers' arrival rate ($\lambda_a^1 = 3600$ ped/h) for all the sizes of stair, i.e., $20 \times 2\,\text{m}^2$, $20 \times 3\,\text{m}^2$, $10 \times 2\,\text{m}^2$ and $10 \times 3\,\text{m}^2$. At lower arrival rate ($\lambda_a^1 = 2500$ ped/h), the blocking occurs only for the stair ($j = 1$) with $W = 2$ m and $L = 10$ m. It is obvious that a smaller size of facilities would lead to congestion issues. But it is observed that at ($\lambda_a^1 = 3600$ ped/h), the blocking occurs at $L = 20$ m and $W = 2$ m, but no blocking has been observed at $L = 10$ mor $L = 3$ m. This means that width of the transfer area is more sensitive to the blocking than length. A small variation in width could result in a blocking effect, while doubling the length of circulation has a no major impact. Due to the splitting topology of the transfer area ($j = 1, 2, 3$), no blocking occurs and similarly, no blocking occurs at downstream (descending) stairs ($j = 4, 5$) due to the splitting of departure rate even though the walking speed is less than the elevated passageways ($j = 2, 3$). The passengers at the egress of MRT station (ascending stairs ($j = 1$)) either proceed toward bus terminal or taxi stop. For CV higher than 1, i.e., at CV (c_a^1) = 50 and CV (c_a^1) = 100, the blocking occurs even for lower passengers' arrival rates, while for CV (c_a^1) = 1 and CV (c_a^1) = 1/30, no blocking occurs. This is due to the fact that at CV = 1, there is a free flow speed; therefore, no congestion occurs at the transfer zone. We can deduce that for all cases, the $M/G(n)/N/N$ technique and TCRP-Report 165 underestimate the blocking probabilities.

Moreover, it is obvious that larger queue length and blocking will increase the mean dwell time of passengers in the transfer zone ($E[T]$). From Fig. 10, we can observe that at upstream stair ($j = 1$), the mean dwell time ($E[T]$) is high due to larger queue length. The large number of passengers interacts with surrounding passengers and decreases their walking speed while traversing the transfer zone. Thus, the slower movement of passengers means longer dwell time. For both lower and higher passenger arrival rates, the passengers' dwell time increases as the CV of the inter-arrival time increases. Due to irregularity and disorientation of passengers' flow at high CV, the dwell time increases. The

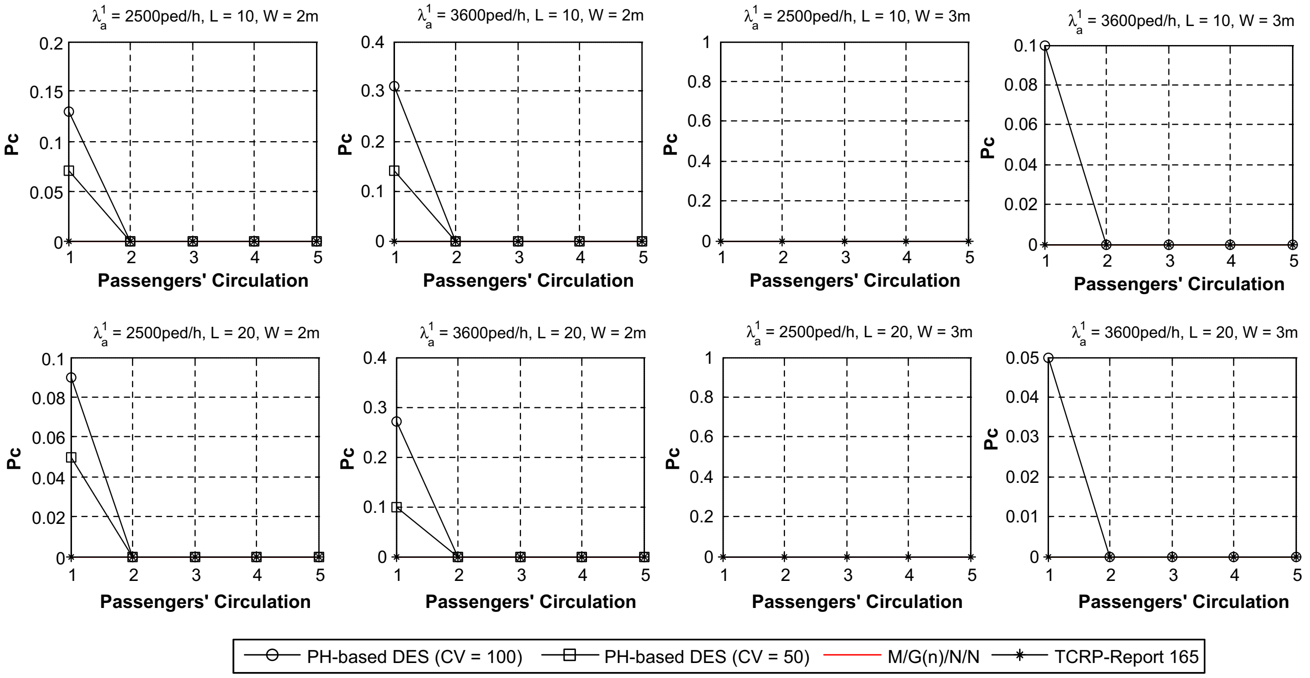

Fig. 9 Blocking probabilities in the transfer zone under different λ_a^1, CV(c_a^1), length and width

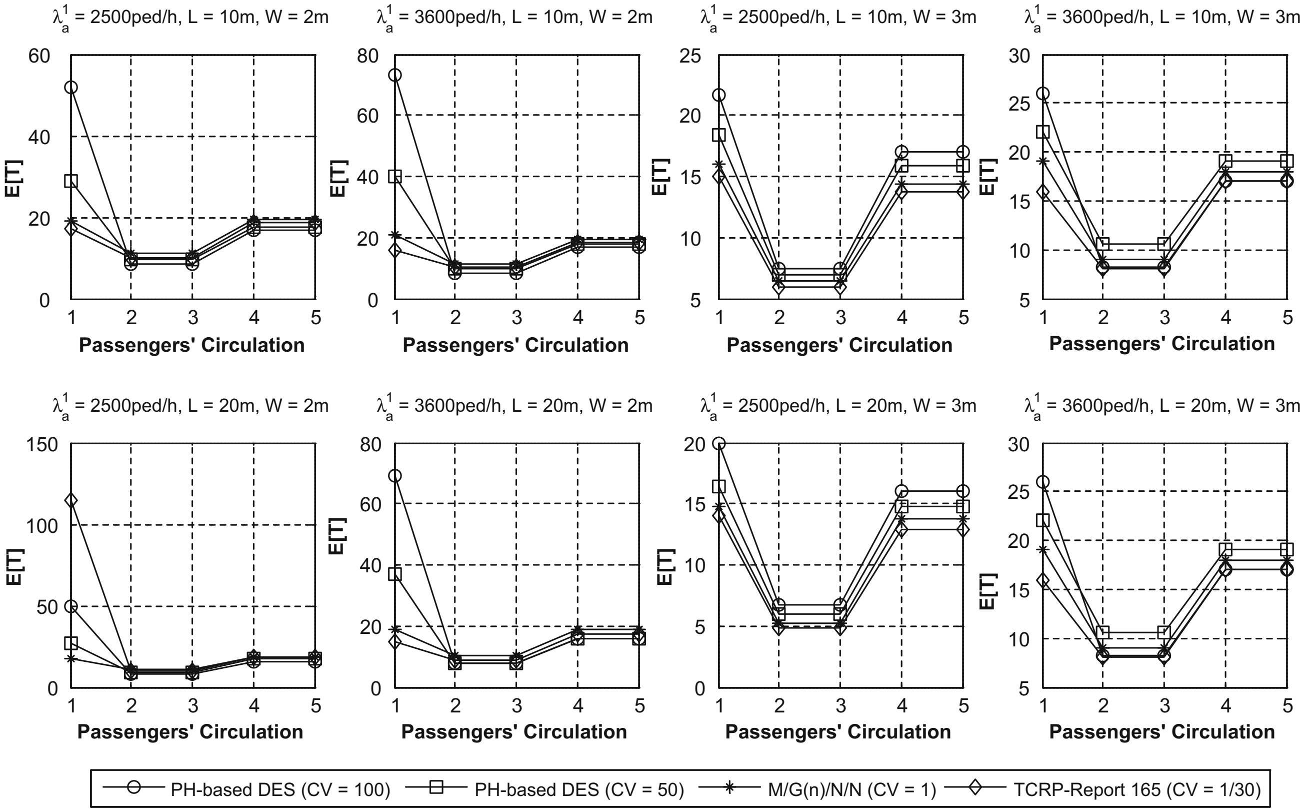

Fig. 10 Mean dwell time in the transfer zone under different λ_a^1, CV(c_a^1), length and width

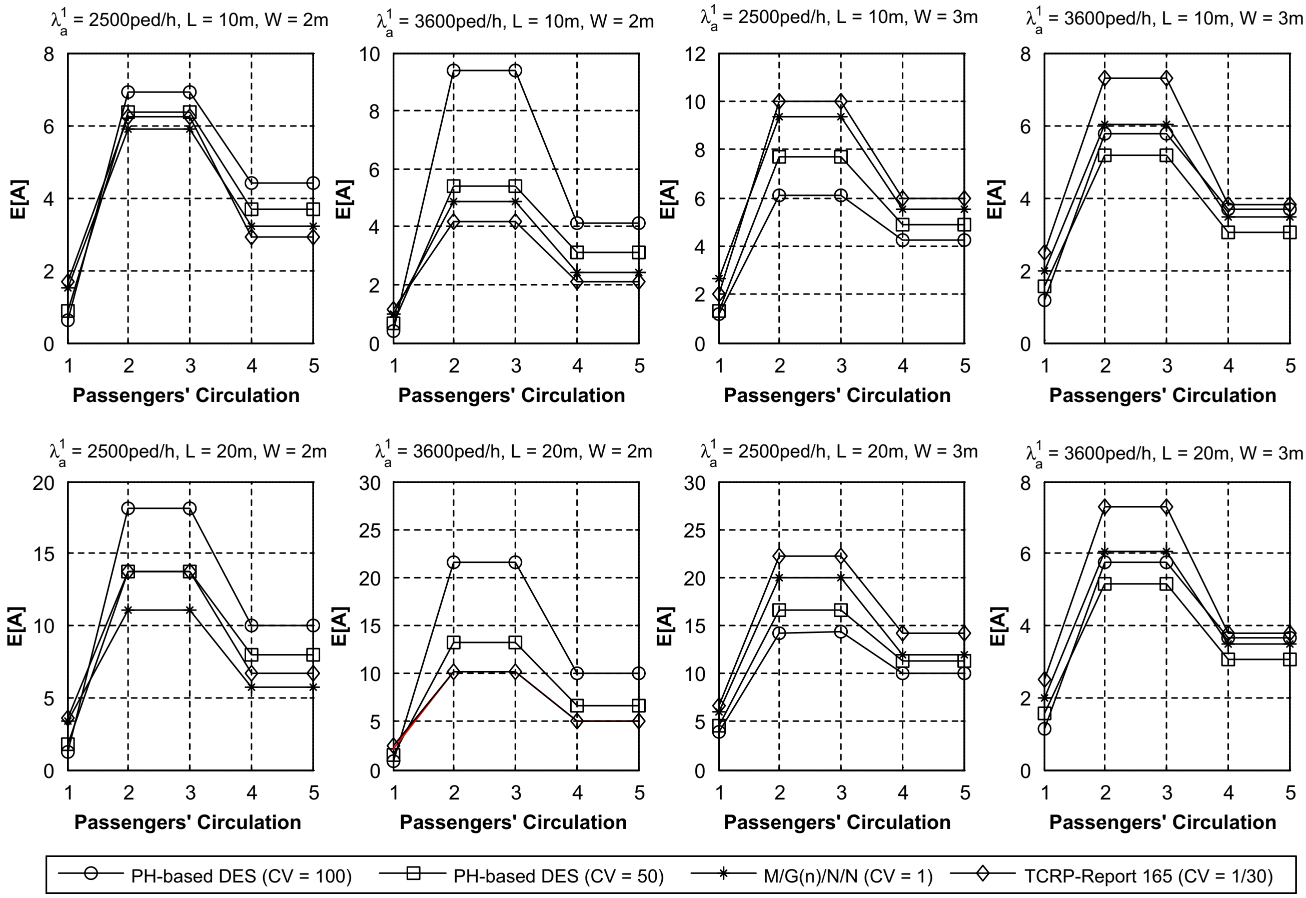

Fig. 11 Mean area occupied per passenger in the transfer zone under different λ_a^1, $\mathrm{CV}(c_a^1)$, length and width

$M/G(n)/N/N$ technique and TCRP-165 Report neglect this effect and therefore underestimate the results. Furthermore, due to splitting topology, the passengers heading toward bus terminal and taxi stop will use separate passageways that reduce the queue length and ultimately the mean dwell time of passengers. Similarly, to safely negotiate the downstream (descending) stairs in the network, the passengers' walking speed slow down causes an increase in the mean number of passengers as well as their mean dwell time.

From Fig. 11, we can observe that all the design parameters play a vital rule in influencing the mean area occupied per passenger ($E[A]$). It depends on the size/proportions of the transfer zone. Therefore, the interpersonal distances among passengers increase with an increase in the area of the passengers' circulation even if the number of passengers in the transfer zone remains constant for all arrival rates and CVs. Obviously, a higher arrival rate causes an increase in the density of passengers in the transfer zone that may result in congestion issues, but changing the length as well as width of the transfer zone will directly affect the density of passengers.

6 Conclusions and Future Work

This paper proposes a PH-based state-dependent DES model for the sensitivity analysis of intermodal transfer zone passengers' circulation in the transit centers. The PH-based state-dependent DES model makes up for the shortcomings in the existing analysis and design techniques (the exponential-based $M/G(n)/N/N$ model and TCRP-Report 165 method) by fully considering the randomness and state dependence as well as (the requirement of) blocking probability. The comparison was first made between the proposed PH-based state-dependent DES model and PH-based analytical model (Zhu et al. [6]) and also with the exponential-based ($M/G(n)/N/N$) DES model by setting the values of $\mathrm{CV}(c_a^1)$ and $\mathrm{CV}(c_s^j)$ equal to 1. Both validation tests have achieved clear consistency.

The sensitivity analysis reveals some major observations: (1) An increase in both passengers' arrival rates (λ_a^1) as well as $\mathrm{CV}(c_a^1)$ of inter-arrival time increases the mean number of passengers and mean dwell time in the transfer zone and reduces the mean area occupied per passenger. (2) Blocking is observed at higher $\mathrm{CV}(c_a^1)$, while no blocking occurs for the existing exponential-based $M/G(n)/C/C$ model and TCRP-Report 165 method, as these techniques ignore CV during the performance analysis. Therefore, these existing techniques underestimate the performance measure results. In addition to the passengers' arrival rate, the CV(c_{a}^{1}) is an important parameter and cannot be ignored in the analysis of the passengers' transfer zone. (3) Width of the transfer zone has played a critical role in effecting all the performance measure values, while length only has an effect on the mean area occupied per passenger. Therefore, width should be given more consideration during the design. (4) Compared to the elevated passageways, the density of passengers is higher at both upstream stairs (ascending stairs) and downstream stairs (descending stairs). It is therefore necessary to use higher width for stairs than passageways to avoid congestion issues on stairs.

The proposed PH-based state-dependent DES model can assist the designers of transit centers in intelligent design regarding the capacity analysis. In the future, vehicular traffic on the streets and highways may also be modeled in the same way. Similarly, the state-dependent arrival rate may be considered in addition to state-dependent service time. To speed up the simulation process, the parallel computing toolbox may be integrated with a simulation module in future work. Furthermore, an integrated simulation–optimization for the optimal configuration of passengers' circulation in transit centers will appear in future publications.

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