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EFFECTS OF EXIT DISCHARGE CONGESTION ON THE EFFECTIVE EVACUATION TIME IN A TYPICAL UNDERGROUND METRO STATION DESIGN

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ABSTRACT

Metro systems are being recognized as an effective and efficient way to solve transport problems in congested cities of the world. In emergencies such as those caused by fire, and power-cut is of utmost importance to have a well organized evacuation of passengers entrapped in an underground metro station building. Observation of fire emergency evacuation situations suggested the importance of managing the crowd on the ticket gates (usually on the concourse level) and the exit discharge on the ground level. The focus of this study is on the modeling of the effect of congestions in the exits discharge area on the effective evacuation time in a typical underground metro station fire. The results suggest that the projected maximum occupancy levels of an open space close to the exit discharge correlates with the movement capabilities of the evacuates at the corridors, stairs, escalators, and other facilities.

INTRODUCTION

Due to the continuous and rapid development of economy, Jakarta experiences dramatic increase of urban population with great impact on the city transportation system.

Rail transit system like the metro system provides large transit volume, low pollution and punctuality and swiftness. Beside the existing lines of on the ground metro system, Jakarta is developing the first underground metro line, right underneath its main road of Jalan Thamrin and Jl. Sudirman. These main roads are one of the Jakarta most densely locations in which have many office towers and public gathering places like the Jakarta main football stadium, the Gelora Bung Karno stadium.

A well organized evacuation of passengers entrapped in an underground metro station building in emergencies such as those caused by fire, and power-cut is of utmost importance. In such conditions it is an ideal to have a jam-free evacuation of the passengers entrapped in a network of corridors, stairs, ticket gates to the exit discharge on the ground floor to the designated assembly areas (Shende, A, 2008). Station capacity can be described as the ability of a station and its associated spaces and facilities to safely and conveniently accommodate and circulate the numbers of people expected to use the station (Goggin, M., 2011). To facilitate that, building codes and regulations prescribe minimum dimensions for corridor widths as well as placement and size of exits depending upon the number of building occupants. These code specifications, such as Standard for Fixed Guide way Transit and Passenger Rail Systems (NFPA 130, 2010), Technical Regulatory Standards on Japanese Railways (MLIT, 2012) aid the designer in providing a certain level of life safety for underground station. But, further efforts has to be put into quantifying the level of safety in terms of effective evacuation time where local characteristics play a great role (Fruin, J.J., 1993).

Fire emergency evacuation situation like in Moscow Metro fire on June 5, 2013 (RT News, 2013) suggests the importance of managing the crowd on the ticket gates (usually on the concourse level) and the exit discharge on the ground level. The focus of this study is on the modeling of the effect of congestions in the exits discharge area on the effective evacuation time in a typical underground metro station fire. The agent-based evacuation simulation tool, Pathfinder (Thunderhead Engineering, 2014) was employed for egress modelling.

This paper will first review the safe occupant evacuation requirements of fire engineering, then introduces a typical design feature of the Jakarta underground metro station, occupant age group and characteristics, and scenarios of metro occupant emergency evacuations.

SAFE OCCUPANT EVACUATION REQUIREMENTS OF FIRE ENGINEERING

For a typical underground metro station, the ability to monitor and control of the whole aspect of train and station operation such as: train movement, signaling, ticketing, ventilation, passenger movement, headways, etc., for both normal and emergency conditions will secure a smooth and safe operation of the whole systems (MLIT, 2012).

In fire engineering analysis, the assessed level of fire risk defines the acceptability of the design. It is therefore essential that all features affecting the total fire risk are included in the analysis. All factors must be quantified, such as selection of design fire, fire development, performance of structural elements, performance of the building occupants, level and reliability of fire safety systems (incorporating both the active and passive measures), intervention of the fire department, and damage caused by fire.

In assessing whether the results are safe, the quantification of the available safe egress time (ASET) and the required safe egress time, must be carried out RSET (Figure 1).

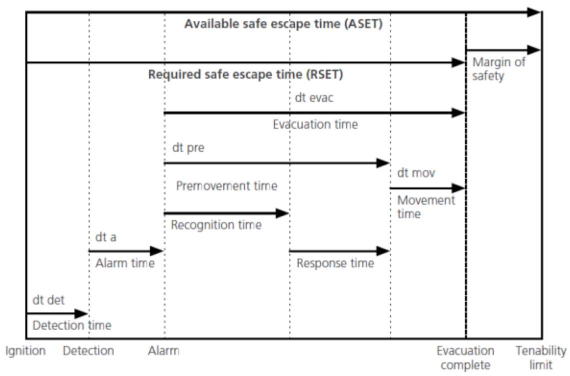

Figure 1: The egress time-line model (Proulx, G, 2008, and Fridolf, K, 2010).

Requirement on safe egress time

For all spaces in a building, the time taken to evacuate the space must be less than the time for the environment in that spaces to become life-threatening, inclusive of a safety margin, so that (Buchanan, A.H., 2001),

$$t_{ev} + t_s < t_{lt} \quad (1)$$

where

t_{ev} is the calculated evacuation time measured from ignition,
t_{lt} is the time for conditions to become life threatening, again measured from ignition,
t_s is the safety margin.

Evacuation time and time for conditions to become life-threatening are both measured from the time of ignition.

Evacuation time t_{ev} is given by:

$$t_{ev} = t_d + t_a + t_o + t_i + t_t + t_q \quad (2)$$

where:
- t_d is the time from ignition until detection of the fire
- t_a is the time from detection until an alarm is sounded
- t_o is the time from alarm until the time occupants make a decision to respond
- t_i is the time for occupants to investigate the fire, collect belogings, fight the fire
- t_t is the travel time, being the actual time required to traverse the escape route until a place of safety is reached including way-finding
- t_q is the queing time at doorways or other obstructions.

The term t_d (detection time) may be determined from computer fire growth models and the threshold value setting of the smoke detectors. The term t_a (time for alarm activation) should be estimated from knowledge of the alarm system or from knowledge of human behavior. The terms t_o and t_i are more difficult to calculate, but should not be taken as less than 30s each. In many real fires, these times have been much more significant than the actual travel time (Buchanan, A.H., 2001).

The safety margin is required to provide an additional safety factor between the calculated evacuation time and the time by which occupants must have escaped. In many scientific literatures and standards, the terms ($t_d + t_a + t_o + t_i$) are recognized as pre-evacuation times.

According to the above analysis, than the bottom line in safe evacuation engineering analysis is to provide a tenable environment within the scope of operation, long enough for occupants to leave the space safety to a place of safety without being unreasonably delayed or impeded. The mathematical description is as follows:

$$ASET > RSET \quad (3)$$

Evacuation Modeling

Evacuation models are often used in the safety design process in the context of the performance-based design approach. They may be employed both to compare different safety designs as well as define the adequate egress strategies of a building Ronchi, E, and Nilsson, D., 2013).

Several evacuation models are now available and widely used. In terms of models characteristics and their suitability for simulating high-rise evacuation scenarios, including multiple egress components, Ronchi, E., and Nilsson, D. (2013) provided a review on a set of evacuation models.

In this work, Pathfinder 2014 (Thunderhead Engineering 2014) was used to simulate underground metro train emergency evacuation. Pathfinder is an agent-based egress simulator that uses steering behaviors to model occupant motion. It consists of three modules: a graphical user interface, the simulator, and a 3D results viewer.

Pathfinder provides two primary options for occupant motion: an SFPE mode and a steering mode. The SFPE mode implements the concepts in the SFPE Handbook of Fire Protection Engineering (Nelson and Mowrer, 2002). This is a flow model, where walking speeds are determined by occupant density within each room and flow through doors is controlled by door width. The steering mode is based on the idea of inverse steering behaviors. Steering behaviors were presented in Craig Reynolds' paper (Reynolds, 1999) and later refined into inverse steering behaviors (Amor et. al., 2006). Pathfinder's steering mode allows more complex behavior to naturally emerge as a byproduct of the movement algorithms - eliminating the need for explicit door queues and density calculations. Although, it is not utilized in this work, the model has Emergency elevators include user-defined kinematic, physical, and operational features. The model includes a way-scripting function that enables the occupants to be directed by performing “go-to” or “wait” actions. The main advantage of this model derives from the possibility to represent the interactions between vertical and horizontal egress components. Limitations are associated with the limited number of input parameters in the elevator kinematic sub-model, such as deceleration rate, etc.

METRO STATION EMERGENCY EVACUATION

Due to the heavily overcrowded population and the situation of underground space, there exist a lot of potential risks during the operation of the metro station. Past accidents have shown that fire accident is still one of the biggest menace to metro system (Shi, C., 2012).

Thus, emergency evacuation in metro stations was identified as a key issue in metro safety in aspect such related to the behavioral and psychological features, such as response time, power, endurance, walking speed, flexibility, panic and other basic data, and how to model these in the evacuation process (microcosmic aspects), and the evacuation strategies, evacuation plan, and how to check the passage capacity and calculate the evacuation time (macroscopic aspects).

As mention earlier, the existing code specifications, such as NFPA 130 (2010), Japanese code (MLIT, 2012) aid the designer in providing a certain level of life safety criteria for underground station. According to the NFPA 130, it is required that the egress capacity of the platform should guarantee to evacuate the platform occupant load in 4 min or less and 6 min for the completion of evacuation. Meanwhile, according to Japanese code (MLIT, 2012), the smoke density during evacuation ≤ permissible smoke density (Cs = 0.1 (1/m). This is equivalent to the visible distance required for an unspecified number of people to evacuate (15 to 20 m). Similar to those of the performance based design, the Japanese code requires several checking procedures to verify evacuation safety for all underground stations in which their characteristics are depend upon the station types, location of fires, type of fires (ordinary or arson fires).

It is mandatory that the width of exit stairs and evacuation passages should guarantee to evacuate all the passengers in the train and waiting on the platform as well as all the working staff away from the platform floor to the point of safety and ultimately to the ground floor. It is also required that the ventilation and smoke exhaust system should be able to provide clear passage for safe evacuation, i.e. permissible smoke density (Cs = 0.1 (1/m) at 2 m height above the floor), longer than the period of evacuation time by a factor of safety.

Overview of Metro Station

The metro station represented in the present simulation work is a two-storeyed underground island station, located near the Jakarta main stadium. This station is typically has 220 m long and 21 m wide. The metro station’s first underground floor is the concourse floor, and the second underground floor is the platform floor, which has an effective platform length of 170 m enabling of 8 cars for future use. There are two escalators and three stairs from the platform to concourse. In addition, there are two firefighter shafts and a vertical lift. The firefighter shafts and the vertical lift are not included for use in the emergency evacuation. The automatic gates in the concourse floor include two groups of exit automatic gates and the side doors. In case of fire, all the entrance/exit gates and side doors should be opened for evacuation. There are four exit passages on the concourse floor leads to five exits on the ground level. In total there are five entrances/exits on the ground level, three of them are equipped with escalators. Figure. 2 shows the 3D layout of the underground metro station studied in this paper. The side walk width on the ground level is 650 cm.

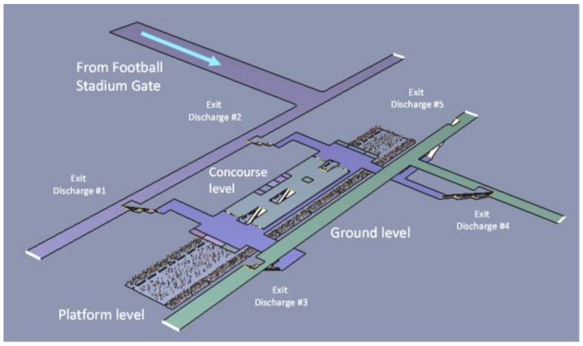

Figure 2: The 3D station layout.

Occupant Characteristics and Distribution

The station studied is located in the main business road, hence it is assumed that the typical occupant characteristics and distributions are as follows:

Table 1: Occupant characteristics and distribution.

	Percentage (%)	Walking speed (m/s)	Shoulder width (cm)
Male	43.9	1.1	46
Female	38.1	1.0	43
Elderly	8.9	0.9	44
Child	9.1	0.85	37
Crowds			
10 to 30 persons standing near the exits.		0.0	46

According to operational conditions there are some possibilities that should be considered during the selection of the number of passenger included in the evacuation studies, namely:

a. Peak hour condition is representing 100% capacity of the cars (1254 persons)
b. One delay train condition is considered at 10 min interval between the two trains. In addition to 100% peak hour capacity, it is assumed there will be 940 persons or 75% of the train capacity are waiting in the platform.
c. Two trains in the same station condition is representing 200% of the cars capacity.
d. Emergency condition is based on an assumption that there is a troubled train with fully loaded passenger to enter to the station (100%), another fully loaded train is at the station (100%), and in addition, there are 940 persons or 75% of the train capacity are waiting in the platform. All passengers inside the station are not allowed to stay and have to be evacuated to the ground level.

Figure 3 shows the graphical representation of the passenger distribution at the platform level. In this work persons in the concourse level are not included in the modeling scheme.

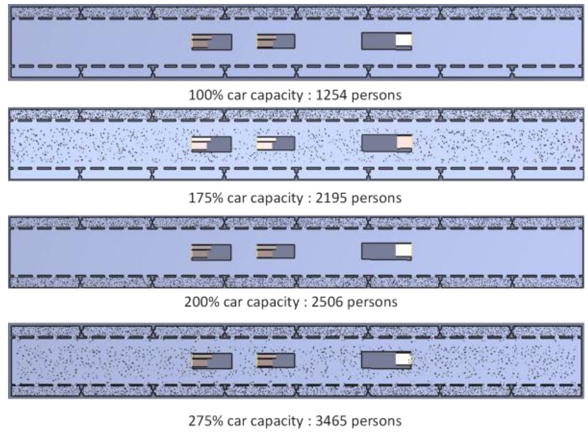

Figure 3: Occupant locations for the four variations of passenger loads.

Responding a Fire Emergency

The Japanese code (MLIT, 2012) and its explanation materials suggested that if a train fire occurs while a train is traveling in a tunnel, it must travel to the next station for evacuation. If the train cannot avoid stopping in a tunnel, passengers can evacuate from the front and rear of the train safely under the instructions of staff. If a fire occurs in a train, the train staff should be notified using the emergency notification system. In preparation for a fire, automatic fire alarms, an emergency public address system, smoke exhaust equipment, fire-extinguishing equipment, etc. are provided at stations. The equipment is centrally controlled by the control room for disaster prevention in the station office and the station is comprehensively monitored. If a fire occurs, a system has been established so that evacuation guidance for passengers and fire-fighting can be performed quickly and properly. If station staff give instructions during evacuation, they must be obeyed.

When a fire happened in a metro station, the main passages during passenger evacuation mainly include train door, platform screen door, staircase and escalator, emergency automatic gate, staff passage (side door), entrance/exit passage, and staircase and escalator at the entrance/exit. During the state of emergency the train door and platform screen door should be fully opened for passenger evacuation, all the escalators from platform to concourse and from the concourse to the ground level is stop and being used as a fixed stair.

The time for emergency evacuation must be calculated as the basis for smoke exhaust system and ventilation design, as well as the installation of fire protection system. If the capacity of the smoke exhaust system is not enough as a result of verification; then counter measures should be provided with the following options (MLIT, 2012):

a. To provide new evacuation route or to widen the route in order to shorten the evacuation time,
b. To enlarge the smoke diffusion volume,
c. To make kiosk, where fire may start, fire- and smoke-proofed and to install sprinkler type fire-extinguishing system,
d. Not to install kiosk from which fire may start, and/or
e. To install other arrangements to secure passengers' evacuation safety.

EFFECTS OF EXIT DISCHARGE CONGESTION

Persons moving through the exit routes of a building maintain a boundary layer clearance from walls and other stationary obstacles they pass. This clearance is needed to accommodate lateral body sway and assure balance. The useful (effective) width of an exit path is the clear width of the path less the width of the boundary layers.

Observations and experiments have shown that evacuation flow speed of a group is a function of the population (Buchanan, A.H., 2001). If the population density is less than about 0.54 persons/m^2 of exit route, individuals will move at their own pace, independent of the speed of others. If the population density exceeds about 3.8 persons/m^2, no movement will take place (Figure 4) (Nelson, H.E., and Mourer, F.W., 2002), until enough of the crowd has passed from the crowded area to reduce the density.

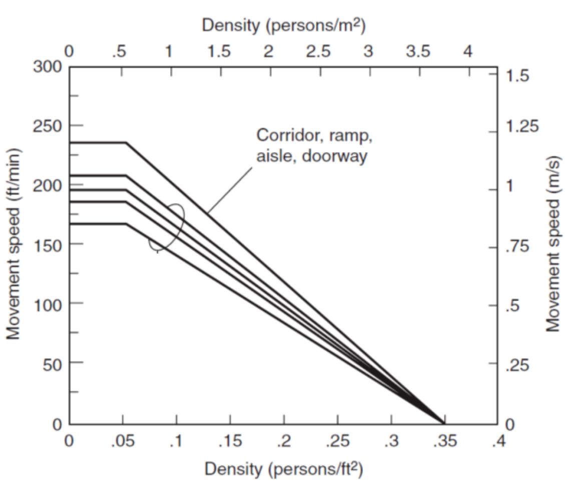

Figure 4: Evacuation speed as a function of density (Nelson, H.E., and Mourer, F.W., 2002)

Although during the design stages, the effective width of the exit passages have been calculated carefully, nevertheless, during a real emergency evacuation, the development of the crowds near the exit discharge locations are unpredictable. Fire emergency evacuation situation like in Moscow Metro fire on June 5, 2013 (RT News, 2013) suggests the importance of managing the crowd on the ticket gates (usually on the concourse level) and the exit discharge on the ground level (Figures 5 and 6).

Figure 5: Congestion on the ticket gate area (RT News, 2013). Photo from instagram user@vladimiri.

Figure 6: Crowd in the exit discharge (RT News, 2013). Photo from twitter user@_katiko.

Scenarios of Crowd Development near Exit Discharge at Ground Level

It is a common observation that moving velocity is a function of pedestrian density. The more jammed the pedestrians are, i.e. the higher the pedestrian density, the lower the flow speed. In the case of the office tower evacuation, the evacuates are directed to the designated assembly points far enough from the exit discharges. The floor warden will then count all evacuates under his/her responsibility. However, In the case of emergency evacuation from the underground metro station, the ultimate point of safety is the ground level with no clear definition of the assembly point areas. It is observed that the evacuates reaching the ground floor decelerate their walking speed due to the release feeling after reaching the point of safety, or due to the crowds of people created at the area close to the entrance/exit points (Figure 6). The individuals in the crowds may simply watch and discuss what is happening during the fire emergency. The crowds can hinder the evacuation processes and other emergency efforts. In this case, the width of the side walk is 650 cm.

To study the effects of the crowds on the congestions developed near the station entrances/exits discharge, four crowd scenarios have been considered as follows:

- Scenario 1: No crowd situation
- Scenario 2: Crowd of 10 persons standing on the area of 10 m^2, 2 m from the exit discharge point.
- Scenario 3: Crowd of 20 persons standing on the area of 10 m^2, 2 m from the exit discharge point.
- Scenario 4: Crowd of 30 persons standing on the area of 10 m^2, 2 m from the exit discharge point.

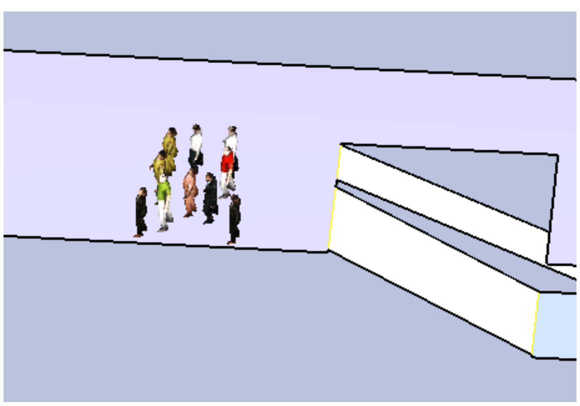

Figure 7: Illustration of the crowd of 10 persons standing close to the station entrances/ exits.

SIMULATION RESULTS AND DISCUSSION

Analysis of Evacuation Time

The typical scenes of evacuating process are shown in Figure 8 for the 100%, 200% and 275% car capacity cases. After the evacuation process was started the passenger moved out of the train cars and flocked onto the platform floor. The evacuates choose exits through the nearest stairs and escalators to escape to concourse level. At 60s, almost all passenger aboard the train have moved onto the platform. However due to the congestion in the entrances of the stair areas, the passengers discharge from the train cars cannot disperse rapidly by entering the staircases.

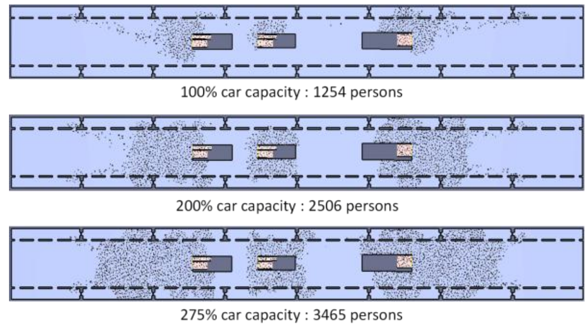

Figure 8: Occupant evacuation scenes in the 60s after the evacuation were started.

Figure 9 shows the comparison of dynamic curves of the persons evacuated from the cars and the platform floor and out to the concourse level (the point of safety) and ultimately to the ground level. The total evacuation times given by the simulation are plotted as bar-charts in Figure 10. In this case the time required by the last person to reach the concourse level and ultimately the ground floor are the moving time only without adding the detection and preparation times prior to the evacuation was started. The fire origin was assumed on the platform level due to arson attach leading to total evacuation of the passengers on the train cars and persons waiting on the platform.

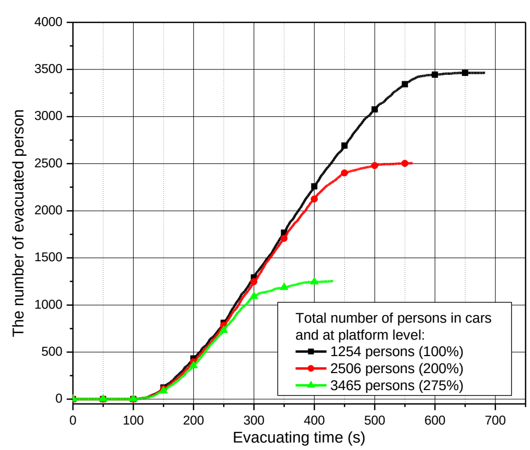

Figure 9: Comparison of the dynamic curves of the persons evacuated from the train cars and from the platform floor to the concourse level and to the ground floor, in the case of fire on the platform.

The results show that the increase of the total evacuation times are solely affected by the increase of total number of evacuates. The curves on Figure 9 line up almost on the same path giving close correlation between the number of the evacuates and the times for reaching the concourse and the ground levels (Figure 10). The results also suggests that besides the congestion at the entrance of the staircases, there is no other congestion along the path from the concourse floor to the ground level.

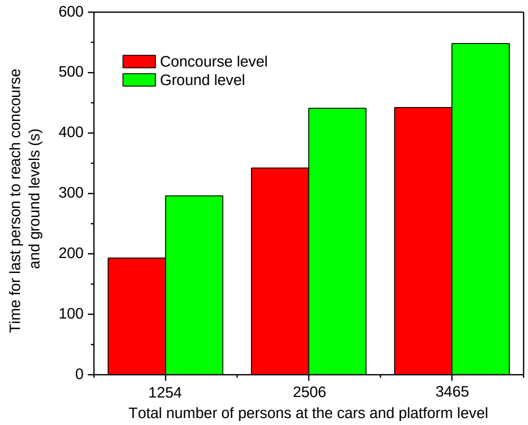

Figure 10: Bar-chart showing the time for the last person to reach the concourse and the ground levels for various total number of persons at the train cars and on the platform level.

Analysis of Evacuation Time affected by Crowd Development near Exit Discharge at Ground Level

To illustrate the effect of congestion at exit discharge location on the effective evacuation times, four scenarios have been formulated and simulated with the worse case emergency scenario having 3465 persons on the platform level (275% train car capacity).

Figure 11 illustrates the congestion at the station exit discharge due to crowd standing close to the station entrances/exits. The crowd eventually reduces the area for escaping. Meanwhile, due to the stream of escapers from the concourse level, the density of the evacuates increases. For Scenario 1, the crowd consisting 10 persons gives little effect on the rate of the escapers reaching the ground level. However, the conditions deteriorates by the increase density of the crowds as shown in results for Scenarios 2 and 3 (Figures 12 and 13). As the pedestrian velocity is a function of pedestrian density, then the more jammed the pedestrians are, i.e. the higher the pedestrian density, the lower the flow speed. It is observed that at a certain high pedestrian density, called the jam density, the pedestrians cannot move that is the flow velocity becomes zero (Scenario 4). The jam density being the density at which the pedestrians or the traffic entities cannot move would depend on the available and effective width of the corridor or the side walk width.

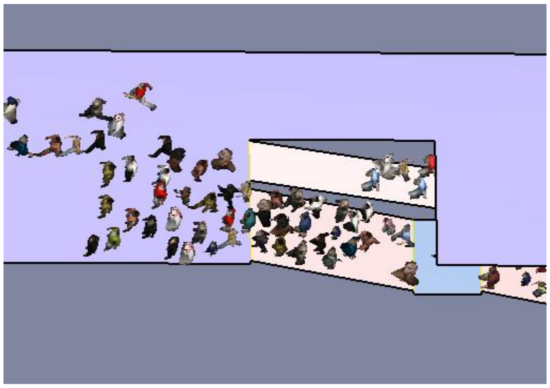

Figure 11: Illustration of the congestion at the station exit due to crowd standing close to the station entrances/exits.

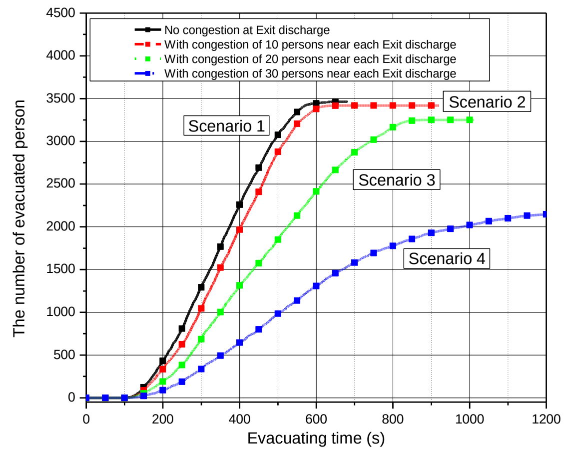

Figure 12: Comparison of the dynamic curves of the persons evacuated from the train cars and from the platform floor to the concourse level and to the ground floor, for various crowd scenarios.

Interesting results are observed when counting the moving times for the evacuates from the platform floor to the concourse floor. The results suggest that the congestions at the exit discharge (Scenarios 1 to 4) do not affect the moving time of the passengers to reach the point of safety at the concourse level. Nevertheless, contrast results are observed where no evacuates can reach the ground floor in the Scenario 4. In this scenario, the crowd of 30 persons standing on the 10 m^2 area close to every exit discharges has created a jam density for passenger to evacuate further to the ground floor from the concourse floor. The passenger are stranded on the concourse floor and on the staircase areas (Figure 13). Therefore, the station operasional management must also take into account the crowd condition on the exit discharge as an integral part of a station emergency respond plan.

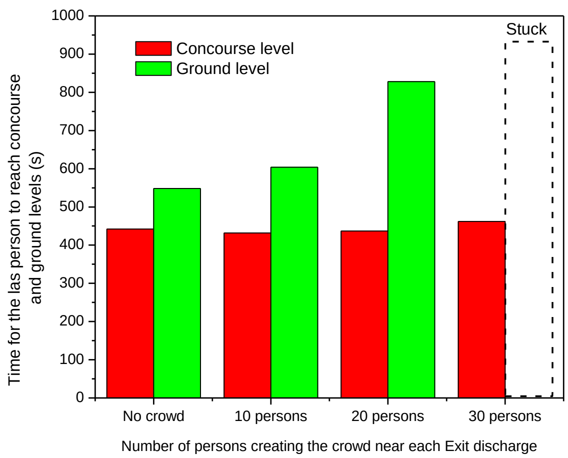

Figure 13: Bar-chart showing the time for the last person to reach the concourse and the ground levels for various crowd conditions. The dotted lines showing no evacuates can reach the ground level.

CONCLUSIONS

Modeling of the evacuation processes of a typical island type underground metro station has been carried out for different number of persons involved and various congestion scenarios at the exit discharge area. Although the evacuation time for evacuates on the platform floor to the point of safety at the concourse level are not affected by congestion at the exit discharge, the results suggested that a great attention should also be put on securing the smooth movement of the evacuates to the so called assembly area close to the exit discharge. A secured area on the ground floor should be designated for this purpose.

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