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Egress Modeling of Evacuation from Railcar - A Case Study

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Abstract: Due to the relatively small, confined space and large occupant loads in railcars, the fire protection and life safety in railcar is greatly concerned in the public transportation industry. The object of this study is to evaluate the emergency evacuation from railcars of a metropolitan railway system in the United States as part of the fire hazard analysis in accordance with NFPA 130, "Standard for Fixed Guideway Transit and Passenger Rail Systems". The evacuation time of the passengers in the railcars to a location (station or exit path) was analyzed by using a computational egress model Pathfinder, and difference scenarios were assigned in different emergency stop conditions that could affect the evacuation time from the railcars. It was found that the evacuation time with full load passengers in the railcars to station is less than 1 minute. Evacuation at the exit path may take much longer (15-20 minutes). This study is useful to assist the emergency management team of railway operation in preparing the emergency plan. Such as (1) station should be considered as the primary location for emergency evacuation; (2) When evacuation at exit path, it is better to first evacuate the railcar where the accident occurred instead of evacuating the entire train simultaneously. The evacuation results are also used to support the fire-resistant design criteria of the floor assembly, which is required to meet 30-minute criteria of ASTM E119 test by NFPA 130.

Keywords: Railcar, Evacuation, Egress Modelling, Fire-Resistance of Floor Assembly

1. Introduction

Rail Rapid transit systems, also know metro, tube, subway or underground, are some of the key public transportation ways in urban areas in United States. Based on the data provided by the American Public Transportation Association's Ridership Reports [1], many cities in United States have railway systems, but not limited to: New York, Los Angeles, Chicago, Washington DC, Boston, San Francisco Bay Area, Philadelphia, Atlanta, Miami, New Jersey, Baltimore, Cleveland and San Juan, *etc*.

In many cases, the floor area of railcars is less than 1000 ft^2 (100 m^2) inside the vehicle, but the occupant loads of full capacity are often calculated with standing passengers at 6 passengers per square meter, which can end up to 250 passengers or more inside a railcar in fully occupied condition. The Fire protection and Life safety (FLS) strategies in the Federal Railroad Administration (FRA) guideline [2] and NFPA 130 [3] are first focused on (1) limitations on the flammability and smoke emission for the materials and assemblies on the vehicles; (2) early fire/accident detection on vehicle; (3) recently some metro railway systems proposed water mist system in railcars to provide active fire protection in vehicle. (4) Certain fire-resistant performance for the floor assemblies, where many electrical equipment is located underneath; (5) emergency evacuation in various stop conditions.

One of the primary concerns of the railway system is whether the passengers in railcars can evacuate out of the vehicle quickly enough and then reach ~~to~~ a safe location, whether the exit doors of railcars and the exit paths along the railway are designed to meet the life safety requirements. This egress analysis is considered as part of the Fire hazard analysis [4] required in NFPA 130 8.4.1.3.1: *"A fire hazard* *analysis shall also be conducted that considers the operating environment within which the seat or mattress assembly will be used in relation to the risk of vandalism, puncture, cutting, introduction of additional combustibles, or other acts that potentially expose the individual components of the assemblies to an ignition source."*

This egress analysis has also been carried out to provide engineering basis to determine whether the 30 minutes fire exposure duration for the floor assembly in the ASTM E119 [5] test can meet life safety requirement intended per NFPA 130 8.5.1.3.2: *The minimum fire exposure duration shall be the greatest of the following:*

(1) Twice the maximum expected time period under normal circumstances for a vehicle to stop completely and safely from its maximum operating speed, plus the time necessary to evacuate a full load of passengers from the vehicle under approved conditions; (2)* 15 minutes for automated guideway transit (AGT) vehicles and low floor vehicles, 30 minutes for all other passenger-carrying vehicles.*

The emergency evacuation from railcars in various operation conditions in the metro railway system is a big concern and challenge to the railway system operations. The concern and challenge are much easier to be addressed by the computer-based egress modeling analysis comparing with the evacuation trials due to the cost in time and money. In this study, the emergency evacuation of the designed vehicles in some operation conditions in the metro railway system in USA was evaluated by the computer-based egress modeling analysis. The software Pathfinder, which was developed by Thunderhead Engineering, Inc., was utilized in this egress modeling analysis.

2. Literature Review

Fire safety in public transportation can be provided by various approaches. The underlying goals embodied in the guidelines and standards (such as NFPA 130) in various countries applicable to passenger guided ground transportation provide for the public safety from fires [6, 7]. The means chosen to achieve the goals maybe different, but the goals (Figure 1) in fire protection are universal:

Figure 1. *Fire Protection Strategy in NFPA 130.*

(1) To prevent the fire or retard its start and spread, material and product performance testing is used to control the fire properties of materials which represent the major fuel loads in the railcar. [8, 9]
(2) To provide occupants early notice of fire accidents, detection and alarm systems notify the passengers to take appropriate actions. These systems also notify designated employees or the public fire service to begin firefighting operations and to assist occupants.
(3) Extinguishing systems, manual or automatic, may also

be provided to control the fire.

(4) Structural fire endurance testing of floors and partitions. Vehicle compartmentation requirements along with limits on the rate of fire growth is intended to minimize the impact of the fire by limiting fire spread. [10]

(5) Training of personnel to react appropriately to fire incidents and system design to facilitate passenger evacuation can play an equally important part in timely passenger evacuation and fire suppression. Overall system design, personnel training, extinguishing equipment, and communication systems support fire service operations.

NFPA 130, "Standard for Fixed Guideway and Transit Systems", which was first published in 1983, is an international fire safety standard widely used for design of transit systems, it applies a holistic approach to life safety from fire and fire protection requirements to include stations, trainway, emergency ventilation systems, vehicles, emergency procedures, communications, and control systems. In railcars, NFPA 130 regulates, through design selection, type of materials, fire safety properties (flammability, combustibility, and smoke production) and potential fire hazards of materials, and fire-resistant performance for floor roof and wall assemblies. [11]

Modern transit station design is a single volume space formed by the passenger platform and contiguous trainway, possible intermediate mezzanine level(s), and continuous connection to the street level above. NFPA 130 requires station to be able to manage fire impact. Controlling the fire in ancillary spaces by means of fire barriers and automatic sprinkler systems and installation of emergency ventilation in enclosed stations serves to manage the fire and manage the exposed. NFPA 130 requires evacuating all passengers from the platform and reaching a point of safety within four (4) minutes and six (6) minutes respectively. A trainway can typically serve as the means of egress for passengers in the event it becomes necessary to evacuate a train. In an enclosed trainway/tunnel, the means of egress includes enclosed exits and cross passageways that serve as points of safety. The maximum distance permitted by NFPA 130 is 2,500 ft. (762m) between exits and 800 ft. (244m) cross passageways respectively. In an urban transit system or intercity passenger rail system, the train population during peak period can be more than 1,000 passengers. The expected required safe egress time to evacuate all passengers from the tunnel into an exit or cross passage can be one hour or longer. Accordingly, evacuation of passengers via trainway is considered the last option in a fire and emergency event.

The egress calculation procedure included in NFPA 130 is a simple hydraulic model. For stations with multiple passenger platforms, platforms on multiple levels, or converging egress routes, the use of a more robust model is often necessary to analyze variations that influence the required safe egress time.

A survey on evacuation was carried out in Great Cairo Metro line [12] based on NFPA 130. The safety of the passengers in the station was evaluated and assessed through the evacuation time. The survey on station evacuation concluded as:

1) The distance to the point of safety and the width of the exit paths are unique key factors for evaluation and varied a lot comparing with the time requirements described above. On the other hand, the height of the ceiling of platform or concourse and the performance of the ventilation system, which are important factors for the tenability condition of smoke, are not considered for normal evaluation at all.
2) The passengers can safely evacuate if the smoke does not interfere with the evacuation. However, the evacuation time for the passengers could be deeply related to the potential fire loads and the density and spread of smoke in station.

Therefore, in a station designed according to NFPA 130 requirement, the evacuation should be achieved in several minutes. It is noticed that in most operation procedures of metro railway system, stations should serve as the primary locations for stop and evacuation if possible.

3. Methodology

This egress modeling analysis was carried out with the software Pathfinder, which was developed by Thunderhead Engineering, Inc. The version of Pathfinder used for this project was the latest official release of Pathfinder from Thunderhead Engineering, Inc. at the time of the study. 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 itself, and a 3D results viewer. More information about the Pathfinder models can be found in the technical reference of Pathfinder [13].

3.1. Principles of the Pathfinder Egress Model

By default, for each time step, Pathfinder evaluates each occupant evacuation, from his/her current position to any of the modeled exits. Each occupant or Pathfinder agent uses path planning, path generation, and path following to reach their destination:

1) Path planning is the process by which Pathfinder determines a plan for moving toward a destination, considering there may be multiple possible paths to reach a destination, each path having a length, other occupants located along the path.
2) Path generation is the process by which Pathfinder determines the path needed to reach the "target" from the current occupant position, considering obstacles such as walls or furniture manually inputted by the user, as well as other occupants.
3) Path following is the process by which Pathfinder determines the components of the path that each occupant follows, in terms of velocity, acceleration, and obstacle / other occupant avoidance.

A Pathfinder provides the options to calculate motion in a

SFPE Mode and a Steering Mode. The SFPE mode implements the flow-based egress modeling techniques presented in the SFPE Handbook of Fire Protection Engineering and the SFPE Engineering Guide: Human Behavior in Fire [14]. For SFPE mode, doors and corridors impose a strict flow rate limit, and occupants can be at the same areas. Also, occupant velocity decreases as room density increases. In steering mode, the occupant behavior follows their seek-curve, which can deviate from the path while approaching to the right direction to their target. For this analysis, the steering mode was utilized for more realistic result.

During an occupant evacuate along paths, the maximum velocity, $\dot{v}_{max}$ is calculate which is figured out with the occupant's current terrain, specified maximum velocity, v_{max}, and the spacing of surrounding occupants. An occupant density, D is calculated with the spacing of surrounding occupants, as indicated below.

The separate reaction steers occupants to keep a desired distance away from other occupants and is utilized when occupants are in an idle state. This reaction works somewhat outside the inverse steering system before considering example directions, the separation reaction calculates a desired direction and distance. The average of occupant separation vectors is as follows:

$$\overline{m} = \frac{1}{n_{occ}} \sum_{i}^{n_{occ}} \overline{m_\iota} \quad (1)$$

Where n_{occ} is the number of occupants by that the occupant would like to separate. If the i^{th} occupant is idle, $\overline{m_t}$, is calculated as:

$$D_{gap} = |\bar{p} - \bar{p}| - r - r_i$$

$$\overline{m_t} = (D_{gap} - D_{sep}) \frac{\bar{p}-\bar{p}_J}{|\bar{p}-\bar{p}_i|} \quad (2)$$

Where $\bar{p}$ is the position of an occupant, r is the radius of an occupant, and D_{sep} is the desired separation distance of the occupant. If the i^{th} occupant is seeking, $\overline{m_t}$ is instead calculated such that it is perpendicular to the i^{th} occupant's direction of travel and its magnitude is defined as:

$$|\overline{m_t}| = r + r_t + D_{sep} - D_{path} \quad (3)$$

Where D_{path} is the occupant's distance to the nearest point on the line tangent to the i_{th} occupant's seek curve. When the movement vector is outlined, the separation behavior works like different inverse steering behaviors.

The avoid walls behavior recognizes walls and steers the occupant to avoid obstructions with them. This behavior reflects a moving agent ahead of the occupant in the direction of the projected point. The cost provided by this behavior is based on the distance the occupant can go in the direction of the projected point. In addition, it is affected by the angle at which the occupant hits the wall. The cost is reduced if the cylinder will hit the wall at a lower angle to the direction where occupant wants to go.

$$D_{min} = \frac{\dot{v}_{curr}{}^2}{2a_{bmax}}$$

$$D_{max} = D_{min} + max\left[\frac{\dot{v}_{curr}{}^2}{2a_{bmax}}, v_{curr}t_{wcr}\right]$$

$$C = \frac{D_{coll} - D_{min}}{D_{max} - D_{min}}$$

$$C_{aw} = \begin{cases} 1, & \overline{d_{slide}} \cdot \overline{d_{des}} \le 0 \\ C * (1 - \overline{d_{slide}} \cdot \overline{d_s}), & \overline{d_{slide}} \cdot \overline{d_{des}} > 0 \end{cases} \quad (4)$$

t_{wcr} is the maximum time where an occupant will react to a wall clash, a_{bmax} is the maximum tangential deceleration, D_{coll} is the collision distance, $\overline{d_{slide}}$ is the direction the agent would slide if they clash the wall, $\overline{d_{des}}$ is the desired travel direction, and $\overline{d_s}$ is the sample direction. The resulting cost is clamped from 0 to 1.

The seek wall separate action steers occupants such that they would like to main a border layer distance away from walls. Like the seek separate action, the occupant's location is anticipated along the sample direction using $\dot{v}_{max}$ and the steering update interval. The closest wall to this location is then used calculate the cost.

$$C_{swsep} = 1 - \frac{d_w - r - bl}{bl} \; G_{swsep} = 1 - \frac{d_w - r - bl}{bl} \quad (5)$$

Pathfinder gives a priority system that works on discrete priority levels allocated to individual agent. At the point when occupants experience different behavior at a similar desired level as their own, they carry on as aforementioned. But, occupants will slightly change the higher actions, if they recognize another agent with a distinct priority ahead of them.

3.2. Limitations of the Pathfinder Model

Pathfinder (as Stated in Pathfinder User Manual) [15] does integrate results from a fire model (2D slices of parameters such as gas temperature, visibility, or CO volume fractions) but it does not automatically adjust the occupant behavior and it does not include 3D results from a fire model. Pathfinder does not provide support for complex behaviors (e g., family grouping) also assisted evacuation can be described by the user.

Dynamic geometry is only partially supported (e g., elevators, virtual escalators, and door opening/closing are supported, but trains and other moving surfaces are not).

4. Evacuation Simulations

4.1. Railcar Configuration

According to the design drawings provided by the railway system, each railcar is 21794 mm long, 3112mm wide. Three (3) exit doors are provided in each car, each door is 1.27 m (50 in.) wide. The locations of the exit doors are indicated in the red circles in the following plan (Figure 2).

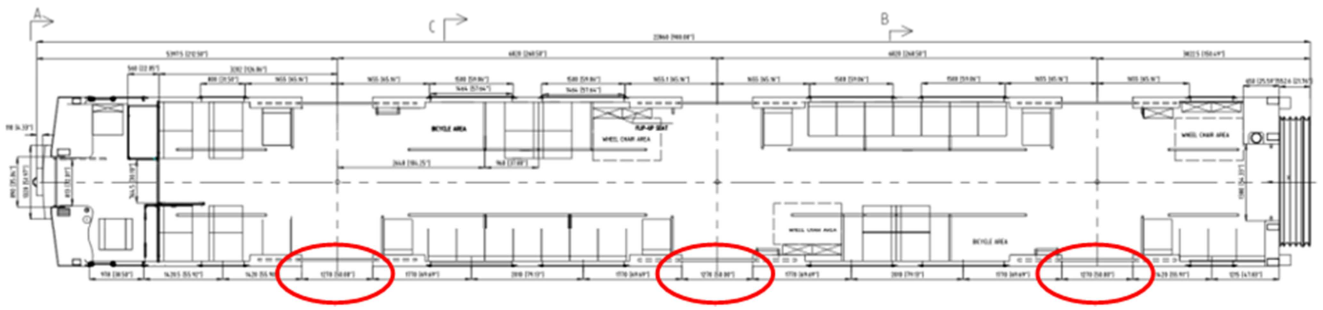

Figure 2. *Railcar Floor Plans.*

Based on the plan, there are 40 seats per car, 3 wheelchair positions, the total number of standees based on full load condition is 205. Therefore, 40+3+205 = 248 occupants are considered as full load condition in the egress modeling analysis.

4.2. Considered Emergency Egress Conditions

Two (2) emergency egress conditions are considered in this analysis:

1) Egress to station platform while the train stops in stations.
2) Egress to raised evacuation walkway/exit path while the train stops out of stations.

For the egress to station platform, it is assumed that the station platform complied with NFPA 130 should be large enough to accommodate all occupants in the train, which has emergency stop at the station.

Per NFPA 130 5.3.2.1* *"The occupant load for a station shall be based on the train load of trains simultaneously entering the station on all tracks in normal traffic direction plus the simultaneous entraining load awaiting trains.*

(1) The train load shall consider only one train at any one track.

(2) The basis for calculating train and entraining loads shall be the peak period ridership figures as projected for design of a new system or as updated for an operating."

Since stations are large enough for all occupants in a train to evacuate to station platform, in this egress scenario, it is assumed that occupants will reach the safety place and not be queuing at the platform once the occupant exit out of the railcar and land on the station platform.

According to the information provided by the railway system, an exit passageway/path is provided in the subway tunnels, which is located at the side of train exit doors with 30 in. in width, at the same elevation as the train floor (and station platform), refer to Figure 3.

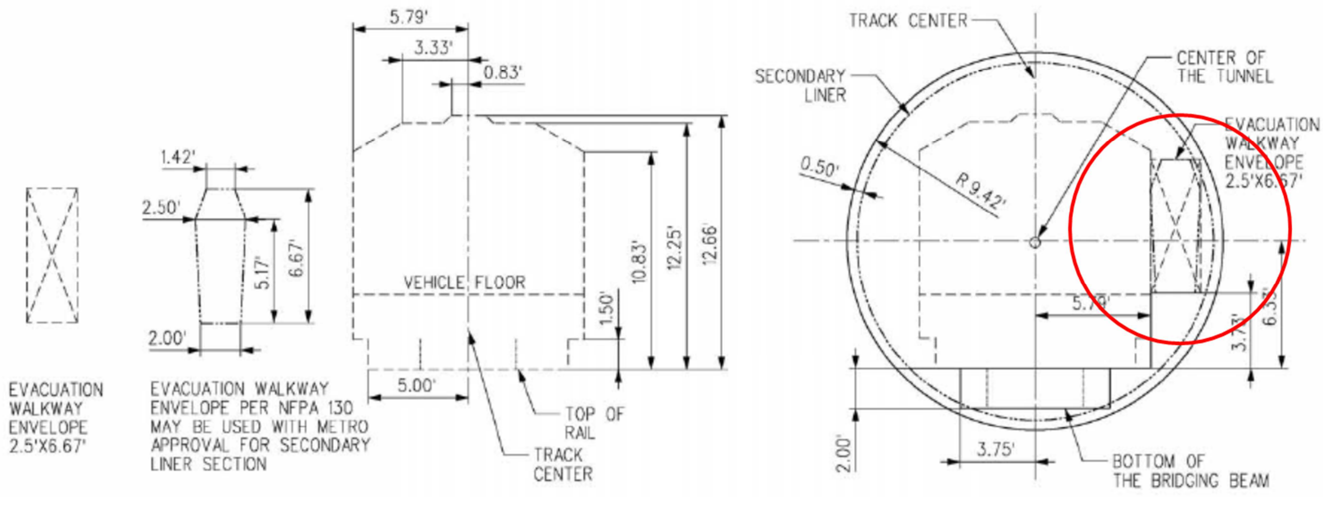

Figure 3. *The Evacuation Walkway in Tunnel (Info in the red circle).*

4.3. Train Combinations

Based on the information provided by the railway system, railcars/vehicles will be operated with the combinations of 2, 4 and 6 railcars/vehicles. The egress modeling analysis was carried out with 2, 4 and 6 railcars combinations accordingly.

Based on the information provided by the railway system, the railcars/vehicles will be operated that the railcars/vehicles are able stop completely and safely from its maximum operating speed (113 km/h) in 22 seconds.

4.4. Railcars/Vehicles Emergency Egress Simulation Results

Based on the different operation conditions and the railcar combinations, the following egress scenarios have been considered in the egress modeling analysis:

1) Evacuation at Station (Figure 4)

a. Scenario 1-1, Exit to Station Platform via side exit doors

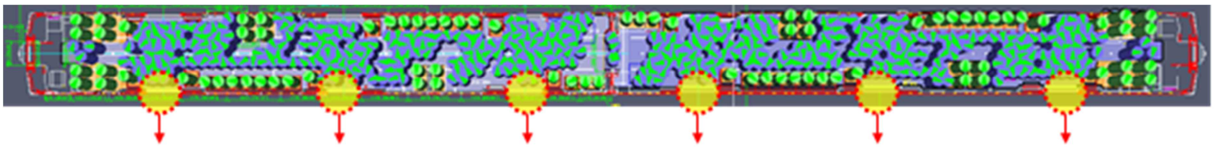

Figure 4. *Egress Model of Railcar to Station with Side exit doors only.*

Since the station platform is assumed large enough to accommodate all passengers in the train with emergency evacuation at the station, two railcars combined train was simulated with three (3) exit doors in each vehicle.

In the modeling analysis, the time for passengers, who may stand at the gangway area, to leave the gangway area is also calculated. The gangway area, which was described by the railway system as the small connection area between two railcars. The gangway area is less than 1.5 in length, and 4~5 passengers were calculated based average occupant density in standing area in the railcar. The location of the gangway in the egress model is illustrated in the following figure (Figure 5).

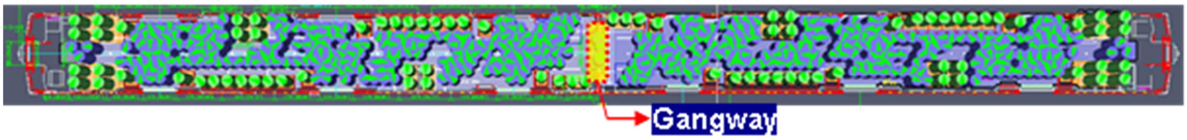

Figure 5. *The Gangway of the Railcar in the egress model.*

It was found that each railcar with full load passengers (248 persons) could evacuate out of the vehicle via the three (3) side exit doors in less than 1 minute (Figure 6).

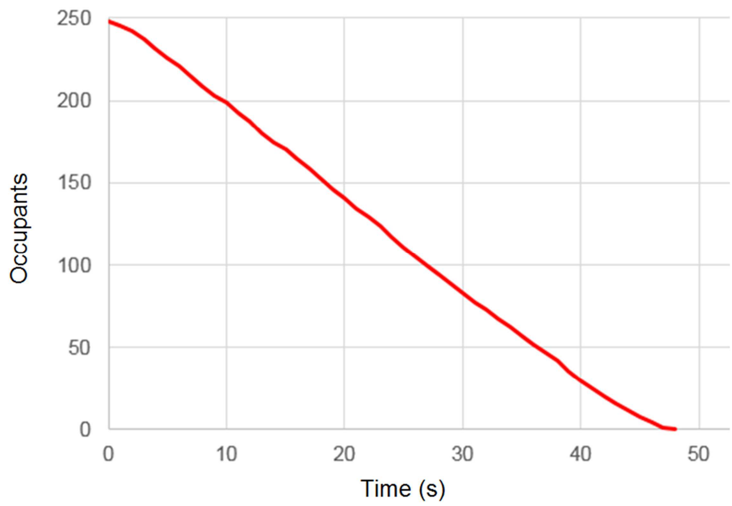

Figure 6. *The egress modeling results of the Railcar to Station.*

b. Scenario 1-2, Exit via side exit doors to Station and the emergency doors at the railcar ends.

According to the design information provided by the railway system, an emergency ladder will be provided at the emergency doors to the track level. The ladder is 30 in. (0.76m) wide and approximately 5 ft. (1.5 m) in height. The egress modeling analysis was performed to evaluate the performance of emergency evacuation with the emergency doors at the front and rear ends of the train.

The egress model is then revised by adding those two emergency-exits (including the emergency ladders) at the train ends. The egress model is illustrated in the following figure (Figure 7).

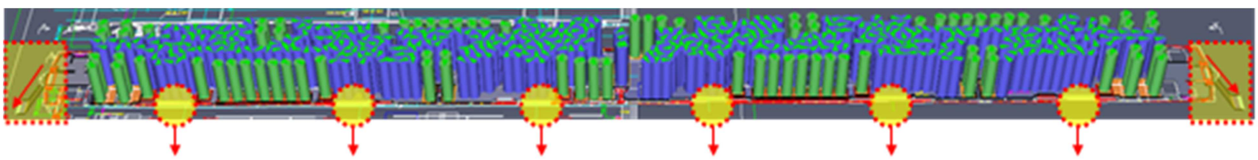

Figure 7. *Egress Model of the Railcar to Station with Side exit doors and the end doors.*

It is found the evacuation time by those two (2) end-exits improved by adding the two end exits is less than 2 seconds in each railcar. Therefore, the improvement to the evacuation by those two (2) end-exits is very limited due to the limited exit capacities provided by the emergency ladders to the track level at the end doors.

2) Evacuation out of Station (in trainway)

Since the contribution by the train end exits is very limited as calculated in the previous scenario, the train end exits are not included and only the side exit doors are considered in the egress scenarios of evacuations out of station. The following egress scenarios assume all passengers exit to the Evacuation Walkway via side exit doors with the combinations of railcars of 4 and 6 cars.

a. Scenario 2-1, four (4) Railcars to evacuation walkway

It is found the evacuation time from railcars to the evacuation Walkway via the side exit doors is less than 12 minutes. The results curve is illustrated in the following figure (Figure 8).

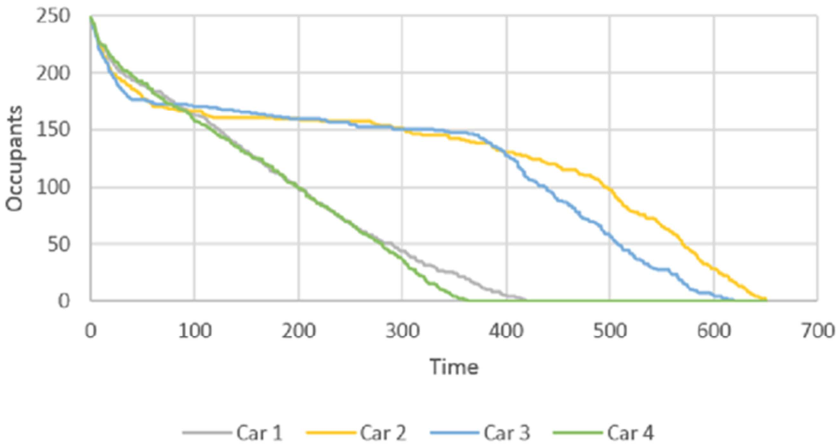

Figure 8. *Egress Results of the Railcar to Evacuation Walkway from four Railcars.*

b. Scenario 2-2, six (6) Railcars to evacuation walkway

It is found the evacuation time from railcars to the evacuation Walkway via the side exit doors is less than 17 minutes. The results curve is illustrated in the following figure.

It was found that the evacuation time with full load passengers in the railcars to station is less than 1 minute. Evacuation at the exit path may take much longer (15-20 minutes). This study is useful to assist the emergency management team of railway operation in preparing the emergency plan. Such as (1) station should be considered as the primary location for evacuation; (2) When evacuation at exit path, it is better to first evacuate the railcar where the accident occurred instead of evacuating the entire train simultaneously.

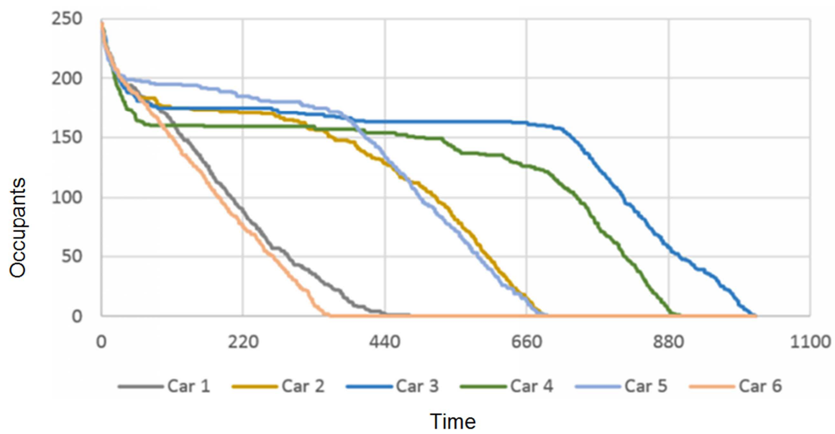

Figure 9. *Egress Results of the Railcar to Evacuation Walkway from six Railcars.*

5. Summary and Conclusion

Based on the egress modeling analysis discussed above, the evacuation from the railcars in the metro railway system in USA has been simulated in different possible operation conditions. It was found that the evacuation time with full load passengers in the railcars to station in less than 1 minute; and the additional exit capacity provided by ladders from the railcar floor level to the track level at the ends of the railcars is very limited.

In the worst case, in which six (6) railcars combined train with full load passengers stops out of station (in trainway), the evacuation time of railcar to the evacuation walkway may need as long as 17 minutes due to the narrow width of the walkway along the tracks. The minimum fire exposure duration required by NFPA 130 8.5.1.3.2, which is calculated by adding twice of the maximum expected time period for emergency stop from the maximum speed (calculated as less than 0.5 minutes), is definitely less than 20 minutes.

Comparing with the 30 minute criteria of ASTM E119 test duration of the floor assembly in the railcars required in NFPA 130, a 50 % safety margin of the railcar evacuation can be well achieved comparing to the criteria of the standard test fire in ASTM E119, even in the worst evacuation condition.

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