Capacity Analysis of a Passenger Rail Hub Using Integrated Railway and Pedestrian Simulation

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Abstract As the level of passenger demand in rail transit systems increases, major railway stations in urban centres face serious capacity issues. Both analytical and simulation methods have been used to analyse complex station areas; however, prior efforts have only focused on either train or pedestrian movements with over-simplified assumptions that do not properly capture the impact of their interaction on capacity. This study applies an integrated crowd and transit simulation platform “Nexus” to simultaneously study the impact of pedestrian and train movements on the system performance of a complex railway station. Unlike other methods such as sequential simulation methods, the integrated simulation platform permits linkage between commercial-grade simulators. Instead of treating each simulator separately, this integrated method enables detailed modelling of how the train and crowd dynamic interact at station platforms. Such integration aims to

explore the interactive effect on both types of movement and enable performance analysis possible only through this combination. To validate the model, a case study is performed on Toronto’s Union Station. Extensive data were collected, processed and input into railway and pedestrian models constructed using OpenTrack and MassMotion, respectively, and integrated via Nexus. Examining scenarios of increased levels of train and passenger volumes, a 9% drop in on-time performance of train operation is observed, while the level of service experienced by passengers on the platform deteriorates significantly due to crowding. Both length and variation in dwell time due to pedestrian movement are recognized as the main factors of performance deterioration, especially when the system approaches capacity limit. The simulation model produces estimates of the practical track-side capacity of the station and associated platform crowding levels, and helps identify locations where passengers experience severe overcrowding, which are not easily obtainable from mathematical models.

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1 Introduction

Passenger rail hubs have become the beating heart of transit systems in large cities. In North America, railway infrastructure was in place before many of the cities that grew around them, placing railway stations in the unique position of being near or in the urban core, with dedicated infrastructure and rights of way. As cities continue to grow and the demand for efficient and sustainable connections to the city centre increases, these hubs are seeing train and

pedestrian volumes that test the functional limits of their design.

Passenger volumes are a major factor in train dwell time at stations [25], and therefore a strong determinant of hub capacity. Expanding railway infrastructure and station size to accommodate this growth is an expensive proposition in many of these cases: Limited additional space in urban rail corridors, historic buildings that require special consideration during renovations, and the high cost of land near these stations all make infrastructure expansion a long-term option for improved capacity. In the near term, station operators must look for ways to manage increased volumes more efficiently [1]. This requires complex and comprehensive analysis of a hub's rail and passenger capacity to better understand the root causes of overcrowding and delay due to congestion.

For a busy railway station, both train and pedestrian movements are vital components of capacity and should be studied together to provide a more complete picture. The complexity of modelling both train and pedestrian movements, even individually, results in studies that focus on one or the other, assuming simplified models for the interactions between the two. For example, fixed dwell times that ignore passenger volumes are often assumed in railway simulation [19], while fixed arrival and departure times for trains are assumed in pedestrian simulation [14].

With an integrated approach that connects two specialized simulation platforms together for simultaneous simulation (OpenTrack for railways and MassMotion for pedestrians), the benefits of both models can be leveraged to paint a more complete picture of station capacity. This paper outlines an approach that leverages sophisticated railway and pedestrian simulation modelling in the context of capacity analysis of a railway hub.¹ To demonstrate the benefits of this approach, the simulation framework is applied to Toronto's Union Station in Canada, a busy and capacity-constrained multi-modal transit hub. The development of the simulation framework includes a more realistic model of passenger alighting which accounts for variations in passenger behaviour observed at terminal stations. The results of this integrated approach are compared with traditional rail simulation methods that use simplified dwell times.

A review of recent approaches to integrated station capacity modelling follows this introduction. The simulation framework is introduced and discussed, followed by an application to Toronto's Union Station. This application demonstrates an advancement in application-ready simulation model development of complex passenger rail hubs, and emphasizes the importance of integrated rail and

pedestrian modelling in our understanding of these complex systems.

2 Literature Review

The study of passenger rail hubs can be roughly divided into two areas of focus: rail operations and pedestrian movement. On the rail side, capacity analysis is concerned with estimating the maximum number of trains that can be operated on a given section of infrastructure over a specified time period, under certain operational conditions [1]. Passenger modelling focuses on maintaining passenger flow for smoother operations with acceptable levels of service. An overview of recent work on both areas is followed by a discussion of literature that considers some form of integration.

Rail analysis studies often examine corridor capacity, discussing factors such as track configuration [12, 26] or the mixture of train types on the railway [7, 15, 30], while station capacity research is more generally focused on urban rail transit such as subways and light rail. Studies on railway capacity are done mainly with commercial railway simulation software platforms such as OpenTrack, RailSys and RTC.² As is common in practice [22], dwell times are assumed fixed or as a static distribution for calculations of rail capacity and do not greatly influence the simulated capacity analysis of the station from moment to moment in the simulation. This stands in contrast to results from analytical regression models that show that dwell time is quite variable, and is sensitive to passenger demand [28, 29, 32].

In passenger modelling, emphasis is placed on smooth flows. Hoy et al. [14] examined passenger flow in Toronto's Union Station using future demand scenarios, indicating that unplanned increases in demand can significantly disrupt passenger flow and station operations. Wang et al. [31] attempted an optimization of passenger flow lines at the Zhongchuan high-speed rail station in China, demonstrating that lengthening walk distances in the station can increase overall flow by reducing interference in the station. Cheung and Lam [5] looked at flow inside Hong Kong's Mass Transit Railway stations, focusing on pedestrian facilities such as stairways. Chen et al. [4] investigated pedestrian crowding at stations on Beijing's Subway Line 1, but did not include busy transfer stations or hubs.

In most pedestrian modelling, train arrivals are typically held static or to a fixed distribution, and emphasis is placed on the effects of flow control within or outside the station.

¹ An earlier version of this work was presented at the 2018 Annual Meeting of the Transportation Research Board. See Pu et al. [24].

² An illustrative example of this is AECOM's capacity analysis of Toronto's Union Station using RTC [2].

One notable exception is King et al. [18], who investigated the effects of varying train arrival times at a busy subway transfer station in Toronto, Ontario, finding that an adjustment of train arrival patterns can lead to an increase in station capacity and passenger flow.

The work by King et al. [18] demonstrates the need for a more direct connection between railway operations and pedestrian crowding, especially in stations that experience high volumes of passengers and are often overcrowded. Research connecting these two well-studied areas is beginning to emerge: Jiang et al. [16] proposed a mathematical model of subway dwell time using parameters such as train headway, boarding and alighting volumes, and the inability of train doors to close as planned due to overcrowding in the vehicle. This dwell time model was integrated into a simulation to dynamically update train departure times as part of a broader line capacity analysis, representing an initial step in integrating passenger and rail-side modelling. A similar approach was demonstrated by D’Acerno et al. [6], where a combined analytical dwell time model and railway simulation with OpenTrack was used to support timetabling development. This analytical model does not capture station layout considerations or provide a detailed level of service attributes for pedestrians, better documenting their experience throughout the station. Srikukenthiran and Shalaby [27] created the Nexus platform, used in this study, which integrates multiple microsimulation packages to model crowding and transit network dynamics. This approach enables explicit microsimulation modelling of the interaction of train and pedestrian flows, allowing for dynamically set dwell times. Hänseler et al. [13] linked pedestrian and passenger movements to create a model that assigns trips throughout a network based on passenger utility that is sensitive to walking speeds in congested conditions and on-board crowding. They assert that “so far, no modeling framework exists that explicitly takes into account the intertwining of traveler dynamics at the network and station level.”

This paper addresses the lack of explicit hub-level interaction between rail and pedestrian dynamics by leveraging the Nexus platform to perform detailed simulation modelling of both people and trains, sharing the information between them as the simulation evolves. This connection is vital for capturing in detail the well-documented influence of passenger volumes on train dwell times, and ultimately the capacity of high volume hubs.

3 Methodology

Integrating two distinct and specialized simulation platforms requires the development of a centralized connection that can speak both of their languages. The Nexus platform

[27] was developed to accomplish just that, acting as a controller between multiple commercially available simulation platforms running simultaneously. Nexus interfaces with individual simulations using their application programming interfaces (APIs). At each time step, Nexus exchanges, evaluates and adjusts information and instructions from these simulation platforms, enabling coordination between them. Nexus tracks and combines data produced by the two simulations, while also allowing them to individually produce results for analysis. A conceptualization of the simulation platform is diagrammed in Fig. 1.

While Srikukenthiran and Shalaby [27] initially used Nexus to model crowds and transit vehicles at a network level in disruption situations, it has been adapted to allow OpenTrack and MassMotion to interface with the platform for rail and pedestrian modelling, respectively. The modelling efforts included in this study include train simulation development, pedestrian simulation development, improved dwell time modelling at terminal stations, and the connection of these improvements into the integrated Nexus platform. These modelling approaches are described in the subsequent sections before being applied to Toronto’s Union Station.

3.1 Railway Simulation

OpenTrack is a planning and simulation tool for railway operations developed at the Swiss Federal Institute of Technology [21]. Through Nexus, OpenTrack is used primarily for accurately simulating railway movements and conflicts in the corridor. OpenTrack enables the modelling of train dynamics, track alignments and grades, signalling systems and track routing. Simulation of train movements follows a specified timetable with delay distributions at predetermined locations. In contrast to spreadsheet or other simplified train movement simulations, multiple performance indicators related to train movements can be tracked and reported, and the realism of the simulated rail corridor is improved.

3.2 Pedestrian Simulation and Station Dwell Time

For the station area, Nexus is programmed to utilize either a simplified dwell time model using Weston’s formula [32] or calculate dwell time endogenously using simulation based on the modeller’s needs. The mathematical dwell time modelling using Weston’s formula is ideal for simple platform structures and is less computationally intensive. A full-scale simulation model for dwell time is ideal for high-volume and complex station structures where conflicting pedestrian flows could occur, and it provides more

Fig. 1 Nexus integrated simulation platform framework and study scope

performance indicators on pedestrian movements as well as level of service.

For the full-scale model, four distinct segments are defined for a dwell time:

- Segment 1: From train arrival to door opening
- Segment 2: From door opening to the exit/entrance of the last passenger
- Segment 3: From the exit/entrance of the last passenger to door closing
- Segment 4: From door closing to train departure

Segments 1, 3 and 4 are considered lost time and are estimated using a distribution that is fit to collected data. Segment 2 is where passenger boarding and alighting occur. MassMotion, an advanced 3D pedestrian simulation and crowd analysis tool developed by Oasys, is applied to realistically simulate these pedestrian movements. The agent-based microsimulation package uses a combination of dynamic route selection and a variant of the social force algorithm to model pedestrian movements. A cost tree is developed for each agent depending on the surrounding environment. Agents apply the social force model every 0.2 s to assess and respond to their current locations and set the new position for the current time step. These processes allow agents to navigate through a building automatically and respond dynamically to evolving operational conditions. To simulate train operations, MassMotion is set to have train doors remain open until a specified number of boarding and alighting passengers at the station have completed their movements. A maximum value can also be defined in the simulation to avoid excessive dwell times. During Nexus simulation, such information is effectively communicated at each time step to allow for an integrated simulation process. First, OpenTrack signals to Nexus when a train arrives at the station. Nexus starts the boarding and alighting process by calculating dwell segments not used by the MassMotion model, and then signals to MassMotion to simulate passenger arrivals at the platform. MassMotion then returns a message to Nexus that boarding is completed, or when a maximum door-open time is reached. Finally, Nexus simulates door closing

events and signals to OpenTrack that the train is ready to depart. OpenTrack allows for the departure of the train after an internal schedule check, and also has the ability to signal MassMotion to hold the train at the station with the doors open.

3.2.1 Passenger Alighting Behaviour

The use of pedestrian simulation allows for the consideration of specific pedestrian movements that occur in special circumstances. At terminal stations, it was observed that a portion of passengers alight immediately, while others alight more slowly upon train arrival. This unique behaviour may be due to the longer dwell time at the station and a lack of perceived urgency by a certain portion of riders to exit the train before door closing. This dwell time can impact passenger densities experienced on the platform and in other areas of the station, as well as actual departure time of trains.

To approximate this behaviour, a piecewise linear model of dwell time is proposed for alighting time at terminal stations. The observed alighting curve is represented by two linear segments of different flow rates for the fast-alighting passengers (f_a) and slow-alighting passengers (f_b). The total alighted passengers ($TP(t)$) as a function of time is given as:

$$TP(t) = \begin{cases} f_a t & 0 < t < \rho \\ f_b(t - \rho) + f_a \rho & t \geq \rho \end{cases} \quad (1)$$

For a given total number of passengers at one train door, the model generates a turning point ρ from the distribution, dividing the population into fast-alighting passengers TP_a and slow-alighting passengers TP_b . For the fast-alighting passengers, a flow rate f_a is generated from the fitted distribution; for the slow-alighting passengers, a corresponding flow rate f_b is generated based on passengers in segment (b) TP_b , using a linear regression method [23]. Figure 2 shows a typical cumulative passenger–time diagram.

3.3 Conducting an Integrated Simulation

Two additional inputs are needed in order to construct the integrated simulation model within Nexus. A General Transit Feed Specification (GTFS) dataset is required to construct the initial network timetable and schedule, extract vehicle trips and divide up the network into its component parts (stations, rail lines and surface network). Simulation software for each component (e.g. MassMotion for specific stations or OpenTrack for certain rail lines) can then be set as required. Additionally, a complete list of each passenger's basic information, including an origin and destination table and departure time, is required.

Other rules and parameters can be defined in Nexus. The schedule delay can be directly applied to the schedule to represent random delays that occur in the real world, a specific priority can be given to certain groups of passengers in the station area, and trains can be specified to adhere to their schedule or they can depart the station as soon as dwell operations are complete. With all the required simulators and inputs, an integrated simulation can be performed with Nexus. A flow chart of a train trip using Nexus simulation is shown in Fig. 3.

4 Application to Toronto's Union Station

To demonstrate the efficacy of the proposed integrated simulation model, an analysis was performed on Toronto's Union Station. Union Station is Canada's busiest multi-modal transit facility, processing approximately 200,000 passengers per day. Opened in 1927, the station has 14 station tracks and 23 passenger platforms (centre and side). Each platform is approximately 350 m long but only 5 m wide and includes multiple staircases, escalators and elevators added for accessibility. Station platform areas are

even narrower in locations where escalators and elevators have been added. Two bypass tracks are located south of the train shed for equipment movements and occasional local freight movements. Today, the station is the central terminal station for a variety of transit services, including GO Transit (a regional commuter bus and rail transit operator), VIA Rail (Canada's national passenger railway carrier) and the Union-Pearson Express (an express train service to Toronto Pearson International Airport). Union Station also connects to the Toronto Transit Commission's (TTC) subway, streetcar and bus services, as shown in Fig. 4. It is located in a central location of the city core, and many arriving passengers travel to their final destination on foot or by bike. Following a commuter peak-period pattern, GO trains carry passengers into downtown Toronto in time for work and transport them out of the core in the evening. Each GO train usually consists of 12 double-decker passenger coaches, accommodating a total of 3000 passengers. Platform crowding is commonly observed during peak hours on the platforms and has been a continued source of frustration and news in Toronto [3, 20].

The rail lines are controlled with a conventional fixed-block signalling system. Major improvements to the station are being implemented, including signalling upgrades, station renovations, and future GO Transit service expansion including SmartTrack and Regional Express Rail [10]. These are expected to bring even more trains and passengers to the station.

For the purpose of this study, a railway simulation analysis using OpenTrack was first performed with considerations to train movements only, with dwell times fixed. An integrated simulation analysis using Nexus was then performed with OpenTrack and MassMotion to capture the interactive effects of both pedestrian movements and train movements on the total capacity at the station

Fig. 2 Representative cumulative passenger–time diagram for a single train door on arrival

Fig. 3 Integrated simulation platform flow chart. Dwell times that are generated (orange boxes) are scenario-dependent

area. The results of various scenarios are compared to demonstrate the differences in simulation outcomes.

4.1 Model Development

The base model was assembled following traditional steps: data collection, model construction, calibration and validation. Further scenario tests, detailed in a later section, were then performed upon successful validation of the base model. The study focused on the Union Station Rail Corridor (USRC), including Union Station and one station prior to Union on each rail line as shown in Fig. 4. The study period was between 8:00 am and 9:00 am, when most train arrivals with the largest inbound passenger volumes occur. All simulations ran from 7:00 am to 10:00 am to include system warm-up and cool-down periods.

4.1.1 Data Collection

Between June 27 and 30, 2016 data collectors boarded trains on one of the seven GO rail lines between 7:30 am and 8:00 am close to the city boundary, travelling into Union Station. GPS location data along each trip were

collected via Android and iPhone applications, while video recordings were made as trains approached Union station to record the path each train took through the Union station ladder system. These on-board recordings were supplemented by additional recordings, taken from an elevated bridge, of the entire area near the station platforms (both west and east interlocking areas) as trains arrived at Union. Train speeds on all track sections were calculated by processing the location data. A total of 30 and 24 (west and east, respectively) of the most commonly used train paths were identified for both revenue and equipment movements.

The GO Tracker website [11] provides the live status of all seven of GO Transit's regional rail lines. It allows for monitoring when trains arrive at stations and when they are running behind schedule (with information provided when the delay is greater than 10 min). Data were collected for each train trip between one of the eight entry stations of this study and Union Station. The collected data included the actual arrival and departure time at the entry station, and the arrival time at Union Station. Reasons for delays were recorded when provided. The data were collected from 6:30 am to 9:30 am from October 2016 to March

2017. The different time period of data collection, compared to the train speed and path data, was not considered an issue, since this collection effort focused only on station delay data. In addition, a longer period was deemed appropriate to generalize the study results.

Passenger volume counts at the concourse level were collected in October of 2016 on weekday mornings between 8:00 am and 9:30 am. This was performed by 10 people using smartphone time-stamped counting apps. Each person was responsible for counting passengers going both ways at one of the nine staircases which connect Union Station's platform 26-27 to the concourse level.

Passenger volume counts at train doors were collected from December 2016 to March 2017. For each train arrival, a random train door was selected for passenger flow counting, since most GO train cars have identical specifications. Additionally, the train door selected was free of barriers (staircases or elevators) on the adjacent platform area to ensure an uninterrupted flow from the train car.

The main purpose of passenger volume counts was to determine the maximum passenger flow rate for critical links at the station, including exit staircases and a typical GO train door. Since these are characteristic of the transit facility, and with an assumption of general passenger behaviour not changing dramatically within a relatively short period, the different time periods of collection were not considered to be an issue.

Dwell time data were collected at the same time as the train door passenger count data. The main goal was to capture the duration of each critical segment of a dwell time at Union Station enumerated in Sect. 3.2.

4.1.2 OpenTrack Model Construction

Data for constructing the infrastructure model were obtained from GO Transit for areas within the USRC (from Strachan Avenue to Don River). Maximum speed limits within and outside the USRC were acquired from the USRC Operation Manual and train speed data collection described earlier. A portion of the infrastructure model is exhibited in Fig. 4.

Train settings were obtained from a variety of sources. Train paths were defined through data collection. Locomotive and engine characteristics, such as tractive effort and motive power, were configured based on a prior report by AECOM on the USRC [2]. GO, VIA and UPX trains were assumed to have 12, 6 and 3 cars, respectively. For the base model, a timetable concurrent with the data collection period was used. While dwell time was determined endogenously for the integrated model, for the OpenTrack-only model, dwell time was fixed at 5 min [2].

Every train was assigned a departure delay from their "entry station" (the station they visited prior to Union);

these delays were pulled from distributions estimated against the collected data for every entry station. For the 25 GO train arrivals specified in the current schedule, six trains were set to continue their trips on a connecting line, while the rest were taken out of service after passengers were allowed to alight. These trains were assumed to leave for the three depots (Willowbrook, Bathurst North and Don Yard). Due to lack of data, it was assumed that each yard had unlimited capacity to accommodate as many out-of-service trains as necessary.

A complication arose from the discovery of unpublished "internal departure schedules" and equipment movements. These consisted of movements that occurred irrespective of the time taken to clear passengers. To reflect these internal departure times, each trip that was set to end service without a departure time on arrival at Union Station was instead set to depart 5 min after the published arrival time. Connecting trips at Union Station were not affected by this assumption. Combined with the earlier assumption of a 5-min dwell time, the resulting dwell would be at minimum 5 min, depending on how early the train arrived at the station.

Calibration Model calibration involved adjusting the signal's performance factor, which affects the accelerating power and maximum speed. The fitted departure delay distributions (based on the collected data) at entry stations across all lines were applied using Monte Carlo simulation to generate delay values for individual train departures. The resulting arrival delays at Union Station were used to validate the model through a comparison with the collected data. Eight repetitions were performed to obtain average results. The metric of on-time performance (OTP) was used to evaluate the arrival delays, given by

$$\text{OTP} = \frac{\text{number of trips within specified range of scheduled time}}{\text{total number of trips scheduled}} \quad (2)$$

GO Transit defines the threshold used in OTP to be no later than 5 min and an overall OTP target of 95% [2]. The OTP at Union Station was found to be 96.4% based on the observed data, excluding major disruptions as indicated by the GO Tracker during data collection. The difference between the overall observed OTP values and the simulated on-time performance (SOTP) was less than 0.1%, and the simulated arrival delay distribution closely replicated the observed delay at Union. The simulated speed–distance diagram also matched observations for each line. These results indicate that the model outputs closely matched the observed values, illustrative of a well-calibrated model.

Sensitivity A sensitivity test was used to determine the maximum train throughput at Union Station to be used later during scenario specification. The GO train volume was incrementally increased until severe arrival delays were

observed. VIA and UP Express services were kept in each scenario at their current train volumes. All GO trains were assumed to have through connecting movements to maximize train throughput. Scheduled travel times between stations were extracted from the current GO schedule, and uniform headway was assumed for each line. At this stage of the analysis, the dwell time at Union Station was fixed at 5 min for each train arrival with no internal departure schedule so that trains would not be constrained. Additionally, all trains followed the identified common train paths. A total of 38 tests were performed as shown in Fig. 5. The system was specified to reach its capacity when the overall SOTP fell below 95%, resulting in a total hourly train volume of 39, up from the 25 trains per peak hour of the base case.

4.1.3 MassMotion Model Construction

A previous 3D Union Station model in MassMotion was developed and calibrated by Arup and applied in this paper with certain modifications as shown in Fig. 4. The complete platform and concourse level were included, and the stopping locations of trains at platforms were assumed to be fixed. Each train car contained one portal to generate inbound passengers and dissipate outbound passengers. Passengers were modelled to enter and exit the station areas via 15 exit portals around the station boundary. The split of the passenger volumes at these exits was set based on cordon counts. Maximum flow rates at critical links (train doors and staircases) were assigned based on the results of the data collection. In addition, custom models for dwell time and passenger alighting behaviour were implemented based on models developed using the collected data and described in Sect. 3.2.

With the collected dwell time data, a statistical analysis was performed for the train arrival to door-open segment; it was found to follow a lognormal distribution averaging 9.38 s. Segment 2 covers the entire duration of passenger flow time; this was modelled endogenously using MassMotion, and not estimated from the data. Both segments 3 and 4 represent the lost time before a train departs the station; however, the data collected also included the “internal departure schedule”. As these segments reflect safety rules or policies (i.e. to check that no passenger was left on the train before heading to the yard), a fixed duration of 2 min for segments 1 and 2 was calculated by subtracting the average duration from the assumed dwell time of 5 min.

As described in Sect. 3.2.1, unique passenger alighting behaviour was observed at Union Station, mostly for trains becoming out-of-service after clearing passengers. The proposed alighting model was used to take such effects into account. Each collected passenger count record at a train door was studied; the turning point was selected based on visual inspection and confirmed by the R^2 values for the two linear segments. Values extracted from the cumulative departure curves included total passengers (n), turning point (ρ) as a lognormal distribution, passengers in segment a (TP_a), segment a flow rate (f_a) as a lognormal distribution, passengers in segment b (TP_b), and segment b flow rate (f_b). The linear relationship between passengers in segment b (TP_b) and the corresponding flow rate f_b is defined as

$$f_b = 0.807(TP_a) - 0.525 \quad (3)$$

The linear relationship was obtained through regression with $R^2 = 0.627$. The model was validated by comparing the average total passenger alighting time (107 s) and maximum total passenger alighting time (221 s) with the observed data (104 and 211 s, respectively). The results

Fig. 5 OpenTrack sensitivity test and model calibration

show a close match. The model indicates that the urgency individuals have to alight is related to the total number that need to alight; that is, they would want to ensure they did not miss their chance to leave before the train departs. This alighting model was implemented in the pedestrian simulation model.

Calibration and Validation Calibration of the model included adjusting queue and waiting costs at platforms and staircases and altering certain agent characteristics such as body radius and direction bias. The calibration procedure focused on passenger flow at each staircase for platform 26–27 and the passenger split among its nine staircases. An iterative process of adjusting the values of parameters was conducted through trial and error. Using the GEH statistical method [17], which compares the simulated and the observed passenger volume at a link, the model was calibrated when at least 85% of the nine staircases for each of the eight repetitions (different seeds) passed the GEH test. To validate the model, the modelled and observed flows were examined, and the result revealed a close match between the two at each of the platform staircases.

4.1.4 Nexus Model Construction

Nexus model construction involves specifying the overall network structure, linking up the individual component simulation models, and specifying the passenger demand origin–destination matrix. Network structure and train schedules were auto-generated based on a GTFS dataset of the USRC network. Departure delays at entry stations, passenger alighting behaviour at Union Station for out-of-service trains, 2-min buffer time for dwell segments 3 and 4, and internal departure time for equipment movement were applied. Passengers' trip data such as origin–destination matrices and arrival times were set using boarding and alighting numbers provided by GO Transit's annual Weekday Cordon Counts report [9]. Passengers departing from all stations were set to arrive at the origins with sufficient time to make their train. A simplified mathematical pedestrian model was assumed for the non-Union stations, as they were not the focus of the study. At the platform level, priority was given to alighting passengers.

Calibration and Validation As Nexus links separate simulation models, the calibration procedure was completed when it was performed for each of the individual component models as detailed in earlier sections. Eight repetitions were performed to obtain average results. To validate the base model, OTP, average delay and passenger volume split among the nine staircases of platform 26–27 were examined. The difference between the observed OTP and total SOTP for Nexus was within 1%. The simulated arrival delay distribution by Nexus closely replicated the

observed delay at Union Station. A maximum of 3% difference was found between the observed and simulated passenger volume split for each staircase. Overall, the model was deemed well calibrated.

4.2 Scenario Analysis and Discussion

The use of Nexus allows train delay values to be extracted from OpenTrack and pedestrian level of service (LOS) to be captured from MassMotion. LOS is based on pedestrian standing space, perceived comfort and safety, and the ability to maneuver from one spot to another. The LOS system is represented by six levels from A to F. LOS A demonstrates an unimpeded condition, while F represents an extremely undesirable state where pedestrian movement is severely constrained [8]. It is important to evaluate LOS F, as it represents extreme overcrowding and could cause severe safety hazards, especially on the narrow platforms and staircases at Union Station.

The system evaluation, therefore, focused on train performance at Union Station and passenger LOS analysis at the platform and each platform staircase. Overall, the performance indicators reported include SOTP, simulated average arrival delay at Union Station, average dwell time, hourly inbound and outbound passenger volume, average percentage of inbound and outbound passengers per second at LOS F, and average duration at LOS F for each inbound and outbound passenger.

4.2.1 Scenario Definitions

With the base model constructed, a series of scenarios were devised in order to show the value of using integrated rail and station microsimulation to properly understand an at-capacity commuter rail hub like Union Station. In particular, the goal was to illustrate the importance of capturing detailed interactions between a complex rail system and a multi-platform station. It was therefore necessary to study how passenger volume increases would impact the train arrival delays as well as passengers' experienced LOS.

The Transit Capacity and Quality of Service Manual (TQSM) [19] offers an approach to calculate the person capacity for a rail route when operated at line capacity based on vehicle capacity and peak hour factor (PHF) as

$$P = TN_C P_C (\text{PHF}) \quad (4)$$

where

P = design person capacity (persons/h),

T = line capacity (trains/h),

N_C = number of cars per train (cars/train),

P_C = the maximum schedule load per car (passengers/car), and

PHF = the peak hour factor (dimensionless)

In this case, since T , N_C and P_C have all been given or determined in the previous analysis, only PHF affects the final person capacity. The PHF is usually determined by the loading standard, accounting for passenger standing space on the transit vehicle. This train-focused approach does not consider the station capacity or passenger movements inside the station. This might not be an issue if the station in question has sufficient capacity; however, it could pose potential safety risks if the platform space is restricted, which is the case at Union Station. To systematically increase passenger volume, the PHF value was adjusted incrementally. Following calculations from the TCQSM, a PHF value of 0.49 was reported for GO Transit. In addition to a baseline scenario replicating existing conditions, the scenarios considered are listed in Table 1, and were chosen based on the following process:

1. GO train volume was increased to the maximum train volume from the OpenTrack sensitivity test (39 trains), with each train carrying equivalent or lower passenger volume than the current levels (PHF = 0.34) (Scenario 1).
2. The passenger volume was increased by adjusting the PHF to 0.49, as stated by the TSQSM for GO Transit (Scenario 2).
3. PHF was increased by increments of 0.05 or 0.1 until severe average arrival delays and long LOS F durations were observed (Scenarios 3–5). This occurred at PHF = 0.7 (Scenario 5).
4. Using this saturated scenario, the 2-min buffer was removed (Scenario 5A).
5. Using this saturated scenario, the 2-min buffer was removed, and all passengers were set to alight immediately on arrival (Scenario 5B)

For the scenarios, outbound passenger volume was substantially smaller and was increased in proportion to the inbound passenger volume based on the ratio in the base scenario. Similar to the sensitivity test in the OpenTrack

model construction, no internal departure times were used in the scenario tests.

4.2.2 Results and Discussion

The results of these scenarios, along with the Nexus base model, are shown in Fig. 6. Since inbound passengers were the main variable adjusted among the first five incremental scenarios, relationships between the inbound passengers and multiple performance indicators are extracted for illustrative purposes in Fig. 7.

For scenarios 1–5, all measures indicate deteriorating performance as passenger volumes increase for both train movements (9% drop in SOTP) and pedestrian movements (three times the length of average LOS F duration for each inbound passenger). The drop in SOTP implies that total passenger delay could grow exponentially considering the volume each delayed train carries.

A more in-depth relationship is observed from Fig. 7. As the inbound passenger volume increases, the SOTP decreases, while the simulated average delay grows exponentially. The standard deviation of average delay increases even faster, which is consistent with the behaviour of certain stochastic queuing systems such as M/M/1. Similar trends can be observed for the average dwell time and its standard deviation, both rising with the inbound passenger volume. It is also noted that the proportion of trips that have a dwell time longer than 5 min increases almost linearly with the increase in inbound passenger volume.

The SOTP drops below 95% just before average dwell time increases above 5 min, which coincides with the fixed dwell time value assumed in the OpenTrack sensitivity test, indicating that the length of dwell time strongly affects the capacity.

It can be observed that the SOTP for the OpenTrack sensitivity test is higher than for Nexus, even when the averaged dwell time in Nexus is less than 5 min. Considering that all other settings between the two are identical, the variation in dwell time caused by pedestrian movements under congested conditions is likely the main contributing factor, and its impact on average delay becomes greater as it increases.

Figure 6 also shows the average hourly total inbound passenger volume (person throughput), which rises as the scheduled inbound train passenger volume increases. The increasing passenger volume also led to a 30% increase in the average percentage of inbound passengers per second at LOS F, as well as an additional 60 s spent by each inbound passenger at LOS F for all platforms and staircases. Similar increases were observed for outbound passengers. Two LOS heat maps in platform and staircase areas are compared in Fig. 8, where a substantially larger LOS F (red) portion of the platform area can be observed in scenario 5

Table 1 Model scenarios considered

Name	PHF	2-min Buffer?	Alighting
Baseline	0.36	Yes	Model
1	0.34	Yes	Model
2	0.49	Yes	Model
3	0.60	Yes	Model
4	0.65	Yes	Model
5	0.7	Yes	Model
5A	0.7	No	Model
5B	0.7	No	Immediate

Fig. 6 Summary of scenario results

than in the base model, indicating that the crowding levels worsened by increasing the train and passenger volumes.

Most of these congested areas were around staircases, the narrowest portion of the platform. The volume of passengers utilizing the system combined with the constrained space, especially at bottlenecks, created jam zones where passengers were unable to proceed along their desired routes, as they were blocked by other passengers. This phenomenon is exacerbated by the uncoordinated scheduling of individual lines, which leads to instances of simultaneous arrival of trains on adjacent platforms. By further inspecting the simulation video playback, it was discovered that many passengers were blocked inside the train car due to the congestion on the platform, especially when two trains arrived around the same time at adjacent platforms, creating immense crowding at the exits. The increased duration at LOS F represents a worsening of the travel experiences by passengers. Considering the narrow

platforms, it could also potentially pose safety hazards at those locations. These results would not be obtained using a traditional analytical dwell time model.

For the final two scenarios (5a and 5b), the 2-min dwell buffer time was removed, and agents were set to alight immediately rather than following the piecewise model described in Sect. 3.2.1, effectively reducing the dwell time. The results in Fig. 6 show increases in SOTP for the two scenarios by 7.6% and 8.5%. Further improvement in scenario 5b suggests a positive impact on train performance if passengers' alighting time can be minimized through repetitive announcements and directions by on-site transit officers. This change did result in a 14-s increase in the corresponding duration at LOS F for inbound passengers, as a greater number alighted at the same time, exacerbating the congestion on the platform. This implies that modifications would be required for the identified

(a) Time-based measures

(b) Percent measures

Fig. 7 Summary of scenario results in relation to inbound passenger volumes

congested area on the platform to ensure an acceptable LOS for passengers under such a policy.

The application of this integrated model allows both train and pedestrian performance to be simultaneously evaluated. This is a considerable advantage over the traditional capacity analysis method that uses only train simulation, which is not capable of producing results related to the platform, particularly accounting for pedestrian movements. It also cannot properly capture the impact of the interaction between train movements and pedestrian movements due to the simplifying assumption of fixed dwell time values. Using railway simulation with a mathematical dwell time modelling approach cannot provide a comparable level of detail, as it fails to consider the crowding effect on the platform due to platform space constraints. The use of integrated simulation can address this shortcoming, accurately representing the interaction between train and pedestrian movements at the station by simultaneously taking both capacity constraints into consideration.

5 Conclusions and Future Work

This paper introduced a methodology and application scenario for a comprehensive capacity analysis of a railway station corridor by considering both train and pedestrian movements using integrated crowd and transit simulation. Results were compared to traditional railway simulation. A 9% drop in train OTP was observed, and passenger average duration at LOS F almost tripled with increasing passenger volume. The impact of passenger volume increases on train OTP is similar to the train volume increase, where OTP drops exponentially as volume rises. Both length and

variations in dwell time were shown to contribute to the deteriorating performance, especially when the system was operating at capacity. Performance improvements were observed by shortening the dwell time through reduced buffer time and faster passenger alighting behaviour. This improvement would need to be coupled with platform modifications to expand the identified congested area on the platform and ensure an acceptable passenger LOS. The determination of the PHF should include not only the loading standard on the transit vehicle, but also the LOS experienced at the station. Passenger volumes would in turn affect overall train delays and pose safety hazards, especially for infrastructure with limited space.

This study demonstrates the advantages of using integrated rail and station microsimulation to analyse a complex transit facility, in particular to account for the two-way interaction between trains and the station at the platform. Integrated simulation permits modelling of train delays resulting from crowd movements during the boarding and alighting process and allows for the pinpointing of bottlenecks in the system, which can occur at both the station and track level. By understanding the dynamics of both pedestrian flow and train operations, especially at the station area, policymakers can fully utilize such an integrated simulation platform to evaluate various operation scenarios, such as train arrival patterns, vehicle configurations, platform layouts and pedestrian flow control measures, so that the best solution can be selected to effectively reduce congestion before committing expensive investment on expanding the infrastructure.

There are, however, still limitations to this research. The capacity of maintenance yards should be considered, and the study scope of the pedestrian movements can be extended to include the entire station area, rather than

Fig. 8 Comparison of passenger-experienced density between base model (a) and (b) Scenario 5. Empty platforms are for VIA Rail, which was not considered due to negligible passenger volumes

(a) Experienced density for baseline model

(b) Experienced density for Scenario 5

being limited to the platform. In addition, a highly simplified model was used in this paper for the observed unique behaviour of alighting passengers from terminating trains, dependent only on the total number of alighting passengers, due to limited access to data. While the model does offer flexibility in determining the final alighting time in this unique situation, additional investigation is needed to more accurately model this behaviour in order to develop effective actions that could reduce dwell time to further enhance capacity.

While Nexus serves as an integration platform that seamlessly combines OpenTrack and MassMotion, its application to an evaluation study similar to the one

reported in this paper requires the knowledge of all component software subsystems: OpenTrack, MassMotion and Nexus. The ability of Nexus to replace the detailed OpenTrack and MassMotion models with simplified or less granular models of train and passenger flows (such as meso/macrosopic flow models) is a desirable goal that is being sought by this study's team.

The Nexus platform can potentially be further applied to various scenarios such as adjusting station layouts, merging platforms and changing the signaling system. The simulation platform could also be used to comprehensively evaluate system performance for a given proposed set of train schedules and projected passenger demand. In

addition, it can be further applied to study other congested or complex transit facilities such as interchange subway stations nearing capacity where the service frequency is high enough to be sensitive to delays.

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Declarations

Conflicts of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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