Discrete event simulation of Maglev transport considering traffic waves

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Abstract

A magnetically levitated vehicle (Maglev) system is under commercialization as a new transportation system in Korea. The Maglev is operated by an unmanned automatic control system. Therefore, the plan of train operation should be carefully established and validated in advance. In general, when making a train operation plan, statistically predicted traffic data is used. However, a traffic wave often occurs in real train service, and demand-driven simulation technology is required to review a train operation plan and service quality considering traffic waves. We propose a method and model to simulate Maglev operation considering continuous demand changes. For this purpose, we employed a discrete event model that is suitable for modeling the behavior of railway passenger transportation. We modeled the system hierarchically using discrete event system specification (DEVS) formalism. In addition, through implementation and an experiment using the DEVSim++ simulation environment, we tested the feasibility of the proposed model. Our experimental results also verified that our demand-driven simulation technology can be used for a priori review of train operation plans and strategies.

Keywords: Discrete event simulation; Train operation simulation; Traffic wave; Discrete event system specification

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1. Introduction

The magnetically levitated vehicle (Maglev) is a new system of transportation wherein a vehicle is levitated a short distance away from a guideway using magnets. The vehicle is propelled with a linear motor. South Korea developed a Maglev running at 110 km/h, constructed a pilot line at Incheon International Airport, and is preparing commercial operation of the Maglev under the national Urban Maglev Program of South Korea [1]. The pilot line is a 6.1 km double track line with six stations via the transformation center, passenger terminal, and international business district, as shown in Figure 1.

The Maglev system is essentially controlled through unmanned automatic operation. Therefore, it is necessary to carefully establish and validate the train operation plans and strategies in advance. Train operation plans are established on the basis of statistically predicted traffic data and train performance simulation data. The statistically predicted traffic data is derived from train route plan. The train performance simulation data contain the dynamic performance of the train, with line and train specifications. In general, the

established train operation plans are represented diagrammatically using a train diagram (DIA). The DIA is a diagram showing a train schedule by the train travel distance with time.

A traffic wave often occurs in real train service due to various factors such as the season, day of the week, and occasional events around the service area. Traffic waves are an important factor for the validation of a DIA design since train operation plans are developed with statistically predicted traffic data. Traffic waves greatly affect the quality of transportation service because they can cause train delays and increase passengers' waiting time. For this reason, demand-driven simulation technology that considers such traffic
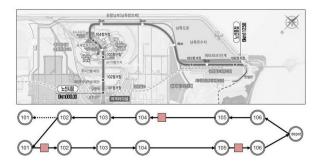

Figure 1. Maglev demonstration line (Incheon International Airport).

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waves must take into account train operational plans and service quality.

Many researchers have investigated the train scheduling problem, and have developed many scheduling techniques. These techniques can be classified into three categories: simulation, expert systems, and mathematical programming [2]. This study is related to simulation.

Various software tools including OpenTrack [3], Bahn [4], and Rail Sys [5] have been used to construct models of train system, and to simulate train operation plans and strategies. OpenTrack uses a mixed discrete-continuous simulation process and object-oriented programming in order to provide a microscopic platform for railroad simulation. Bahn is a shareware program used for designing and testing train or streetcar transportation networks. Rail Sys is a software system that integrates a timetable and infrastructure manager with synchronous microscopic simulation. An alternative method capable of single train traction calculation, multi-train simulation, and timetable assessment is described in [6]; however, they did not consider traffic waves fluctuating with time [7].

The use of discrete event modeling techniques for train scheduling has been suggested in several studies [7-9]. Interstation Train Movement Simulation (ITMS) package is a train operation simulator developed for evaluating and optimizing various operation strategies of a train signaling system [8]. A train signaling system controls the interval between preceding and descending trains. ITMS was developed using discrete event modeling and object-orient programming technologies. However, ITMS does not consider continuous traffic waves. Grube et al. [7] attempted to increase the operation efficiency of a subway in Santiago, Chile. For this, they performed a train operation simulation considering passenger demand, and evaluated the operation strategies of the control system. The system's behavior is influenced by the passenger arrival rate which varies with time and thus the system's behavior is very difficult to predict analytically. For this reason, they represented major activities, including the train's arrival and passenger boarding, as events, and simulated these behaviors with an event-driven dynamic simulator. However, their train operation model assumed that the train has a constant speed. A train operation model should provide a continuous train speed profile that considers acceleration for a realistic and accurate simulation. Paolucci et al. [9] tried to integrate object-oriented modeling and discrete event modeling with the aim of modeling a complex subway system. Through this integration, they developed a simulator to generate a subway operation schedule and signal control strategies. They focused on a schedule based on a constant passenger occurrence ratio, and thus did not consider variation in passenger demand with time.

We propose a method to simulate passenger transport on the Maglev considering continuous demand changes. For this purpose, we employed a discrete event system (DES), which is suitable for modeling the behavior of railway passenger
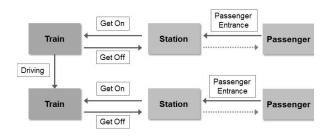

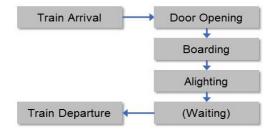Figure 2. Concept model of boarding/alighting with train movements.

Figure 3. Passenger boarding/alighting procedure.

transportation [10]. To model the DES for the Maglev, a discrete event system specification (DEVS) [11] was used. The DEVS effectively describes the complex system behavior as a hierarchical structure using a mathematical formalism based on set theory. In addition, we developed a Maglev driving simulation program that simulates the aforementioned discrete event model using the DEVSim++ [12] simulation environment. Through simulation and experiments, we tested the feasibility of the proposed model and verified that our demand-driven simulation technology could be used for a priori review of train operation plans and strategies.

2. Maglev transport simulation system overview

The goals of this study are to simulate the train operation and the boarding/alighting of passengers and to record the time of each event in order to compile statistics. For this simulation, we assumed that the pilot line is a 6.1 km double track line with six stations for the Maglev; continuous wave traffic is generated from each station; and four trains are in operation.

Basic boarding/alighting and train movements can be conceptually expressed as shown in Figure 2. The train, stations, and passengers are crucial model elements for the system. A train is run on the designated tracks based on signal control, experiencing such discrete events as the arrival at and departure from the station. When the train arrives, the doors are opened and passengers get on or off the train. Then, the train departs after a predefined standby time, as shown in Figure 3.

This boarding/alighting process may also be modeled as a discrete event. The entrance of passengers into each station and the process of keeping the train standing by can be modeled using a random process and queuing: the discrete event model provides an appropriate modeling method, encompassing the train's operation and passenger boarding/alighting.
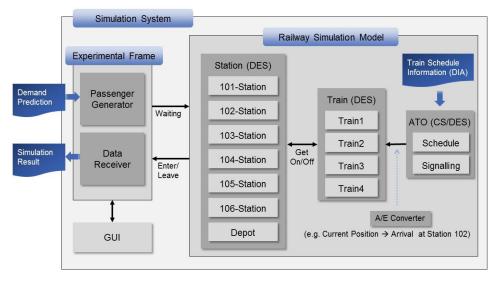
Figure 4. Architecture of the entire simulation system.

The architecture of the entire simulation system is shown in Figure 4. First, unmanned automatic operation is carried out on the basis of predefined operation information, and the model that simulates passenger boarding/alighting for each station is defined as a railway simulation model. This model includes automatic train operation (ATO) that is responsible for the scheduling and signal control of the trains and stations. Trains and stations transmit or receive messages related to passenger boarding/alighting. The behaviors of trains and stations can be expressed as changes in the internal status due to discrete event inputs and outputs. Therefore, the DES model is suitable in this case. ATO is modeled using the continuous system (CS). An analog-to-event (A/E) converter is used to generate station arrival events based on knowledge of the current location of the train.

A passenger generator is needed for passenger generation modeling, which is carried out as a random process on the basis of a demand forecast. A data receiver is used to collect and statically process all the data related to train operation and passenger boarding/alighting. These two tools can be abstracted into an experimental frame model that generates various inputs and analyzes outputs for the railway simulation model. The experimental frame model can also be linked to a graphical user interface (GUI) that is capable of monitoring the entire simulation process and the data involved.

3. System modeling based on DEVS formalism

As suggested by Zeigler [13], the DEVS formalism provides a mathematical framework to divide a discrete event system by module, and model it hierarchically. The DEVS formalism expresses the dynamic equations of the system on the basis of set theory, and uses atomic and composition models to enable structured modeling. The system's behaviors are expressed as state transition processes over time with individual atomic models sharing events with each other. Composition models are responsible for the delivery of

events between individual component models. Using the DEVS formalism, atomic models are expressed as three sets and four functions that describe the behavior of a discrete event system whose internal condition is changed or altered by external inputs over time. In-depth descriptions of DEVS formalism, modeling, and applications on this basis are provided in [13].

List 1. Atomic model in DEVS formalism.

$M = < S, X, Y, \delta_{int}, \delta_{ext}, \lambda, ta>$
S : sequential states set
X : input event set
Y : output event set
δ_{int} : internal transition function $(S \rightarrow S)$
δ_{ext} : external transition function $(Q \times X \rightarrow Q)$
λ : output function $(Q \rightarrow Y)$
ta : time advance function $(S \rightarrow Real)$
$Q = \{ (s,e) \mid s \in S, \text{ and } 0 \le e \le ta(s) \}$: state of M

DES is a suitable technique for modeling railway traffic control systems because trains follow defined paths and interact via the signaling system at discrete times [10]. Moreover, DES is particularly useful in systems characterized by random processes [14] and queuing [15]. Therefore, we adopted the DEVS formalism to model Maglev operation and the passenger boarding/alighting system, which is expressed as a DES. For this purpose, we abstracted the simulation model
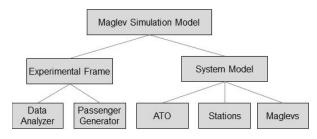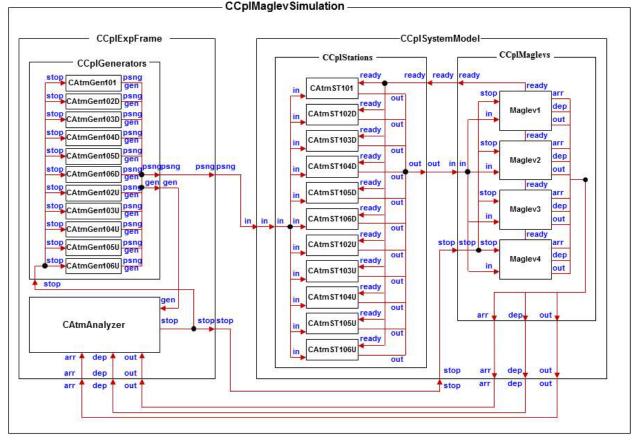

Figure 5. System decomposition tree.

Figure 6. DEVS diagram for Maglev simulation.

into several hierarchical models using a system decompose-tion tree, as shown in Figure 5. The overall system model consists of data analyzer, passenger generator, ATO, stations, and Maglevs. The data analyzer, passenger generator, stations, and Maglevs were modeled as the DES, and the ATO was modeled as a continuous system. The ATO is described in Section 4.2.

Based on this system classification, we defined atomic models and composition models in DEVS formalism, and designed arrangement and message exchange relationships among these models. The overall system model diagrammed in DEVS formalism is shown in Figure 6. CCplMaglev simulation is a root composition model, and is composed of CCpleExpFrame and CCplSystemModel composition models. The CCpleExpFrame model is responsible for generating passenger data and analyzing simulation results. The CCplSystemModel simulates passenger boarding/alighting for each station. At the lower level, there are three composition models: CCplGenerators, CCplStations, and CCplMaglevs. CCplMaglevs consists of four atomic models representing four trains (Maglev1 to Maglev4). CCplStations consists of 11 atomic models representing 11 stations (CAtmST101 to CAtmST106U, sixup-way stations and five-down-way stations). CCplGenerators consists of 11 atomic models representing passenger generators for 11 stations (CAtmGen101 to CAtmGen106U).

CAtmMaglev, an atomic model representing the Maglev, has six system states: operation underway (Driving), doors open (Open), passengers alighting (GetOff), passengers boarding (GetOn), standby (Idle), and doors closing (Close). In the Driving state, the current location of the train is updated by ATO, which is renewed each cycle. Upon arrival at the station, the arrival output (Arr) is generated, and the system state is switched to "Open." When the doors are opened, a passenger alighting output (Out) is generated, and the input for new passengers (In) is fed after all passengers disembark. Once all passengers have exited the train, the standby process is carried out before door closing, departure, and subsequent generation of the departure output (Dep). When all passengers have disembarked, a signal that passenger boarding can initiate (Ready) is sent to the station, which then releases the passengers.

A DEVS diagram that represents the boarding/alighting procedures for passengers in the Maglev is shown in Figure 7. Each system state is shown by a circle symbol and a time advance parameter. Internal state transitions are represented by dotted lines; external state transitions by solid lines; external inputs that induce external state transitions by question marks; and internal outputs resulting from internal state transitions as exclamation marks.

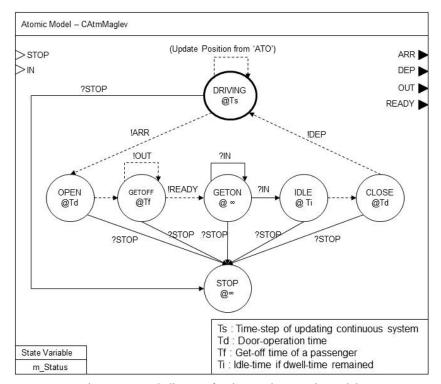Based on these system behaviors, we described the DEVS formalism as follows:

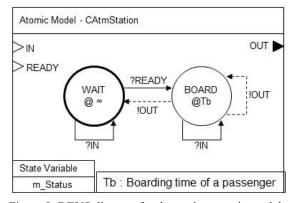Figure 7. DEVS diagram for the Maglev atomic model.

Figure 8. DEVS diagram for the station atomic model.

List 2. CAtmMaglev atomic model in DEVS formalism.

CAtmMaglev = $<S, X, Y, \delta_{int}, \delta_{ext}, \lambda, ta>$
  X = {stop, in}
  Y = {arr, dep, out, ready}
  S = {DRIVING, OPEN, GETOFF, GETON, IDLE, CLOSE, STOP}

$\delta_{ext} : Q \times X \rightarrow Q, Q = \{ (s,e) \mid s \in S \text{ and } 0 \leq e \leq ta(s) \}$
  δ_{ext} ((DRIVING, t), stop) = (STOP, 0)
  δ_{ext}((OPEN, t), stop) = (STOP, 0)
  δ_{ext} ((GETOFF, t), stop) = (STOP, 0)
  δ_{ext} ((GETON, t), stop) = (STOP, 0)
  δ_{ext} ((IDLE, t), stop) = (STOP, 0)
  δ_{ext} ((CLOSE, t), stop) = (STOP, 0)
  δ_{ext} ((GETON, t), in) = (GETON, 0) (if not last passenger of station)
  δ_{ext} ((GETON, t), in) = (IDLE, 0) (if last passenger of station)

$\delta_{int} : Q \rightarrow Q$
  δ_{int} (DRIVING, Ts) = (DRIVING, 0) (Ts : time-step of updating continuous system)
  δ_{int} (DRIVING, Ts) = (OPEN, 0) (if maglev arrived at a station)
  δ_{int} (OPEN, Td) = (GETOFF, 0) (Td : door-operation time)
  δ_{int} (GETOFF, Tf) = (GETOFF, 0) (Tf : get-off time of a passenger)
  δ_{int} (GETOFF, Tf) = (GETON, 0) (if last passenger of maglev)
  δ_{int} (IDLE, Ti) = (CLOSE, 0) (Ti : idle-time if dwell-time remained)
  δ_{int} (CLOSE, Td) = (DRIVING, 0) (Td : door-operation time)

$\lambda : Q \rightarrow Y$
  λ (DRIVING, Ts) = arr (if arrived)
  λ (GETOFF, Tf) = out (if passengers in maglev)
  λ (GETOFF, Tf) = ready (if no more passengers in maglev)
  λ (CLOSE, Td) = dep

$ta : S \rightarrow R$
  $ta(S)$ = ∞, S = {GETON, STOP}
  $ta(S)$ = Td, S = {OPEN, CLOSE}
  ta(GETOFF) = Tf
  ta(IDLE) = Ti

CAtmStation, an atomic model representing the station, is defined as a typical queuing model. CAtmStation involves the entrance of passengers and the waiting condition on the station platform, as shown in Figure 8. The station acts as a buffer between a passenger generator and the trains, and it can be implemented by a first in-first out (FIFO) queuing model.

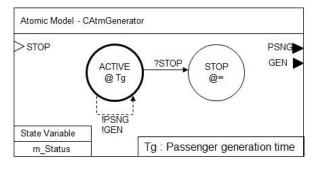When "Ready" input is received from the train, the station

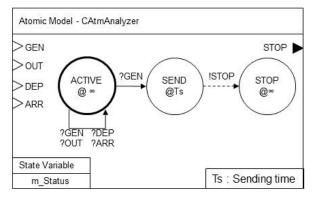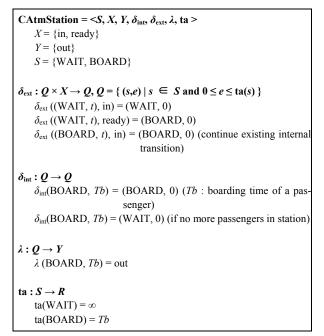Figure 9. DEVS diagram for the passenger generator atomic model.

Figure 10. DEVS diagram for the analyzer atomic model.

changes its state to passengers boarding (Board) from the waiting condition (Wait), and subsequently generates a boarding signal (Out). Once all passengers have boarded the train, the station returns its state to the waiting condition (Wait). The passenger entrance input (In) can be processed in both the "Wait" and "Board" states. Based on the boarding /

alighting process in a station, we describe the DEVS formalism as follows:

List 3. CAtmStation atomic model in DEVS formalism.

$$CAtmStation = \langle S, X, Y, \delta_{int}, \delta_{ext}, \lambda, ta \rangle$$
$X = \{in, ready\}$
$Y = \{out\}$
$S = \{WAIT, BOARD\}$

$\delta_{ext} : Q \times X \rightarrow Q, Q = \{ (s,e) \mid s \in S \text{ and } 0 \leq e \leq ta(s) \}$
$\delta_{ext} ((WAIT, t), in) = (WAIT, 0)$
$\delta_{ext} ((WAIT, t), ready) = (BOARD, 0)$
$\delta_{ext} ((BOARD, t), in) = (BOARD, 0)$ (continue existing internal transition)

$\delta_{int} : Q \rightarrow Q$
$\delta_{int}(BOARD, Tb) = (BOARD, 0)$ (Tb : boarding time of a passenger)
$\delta_{int}(BOARD, Tb) = (WAIT, 0)$ (if no more passengers in station)

$\lambda : Q \rightarrow Y$
$\lambda (BOARD, Tb) = out$

$ta : S \rightarrow R$
$ta(WAIT) = \infty$
$ta(BOARD) = Tb$

When CAtmGenerator in the Experimental Frame comes to active state (Active), it generates passengers randomly and transmits the output to stations (CCplStations) or the data analyzer (CAtmAnayzer). In addition, when CAtmGenerator receives the cease command (Stop), it transitions itself into the stop state (Stop). CAtmAnalyzer gathers various train operation data that has been outputted from CCplSystemModel as well as passenger generation information from CAtm-
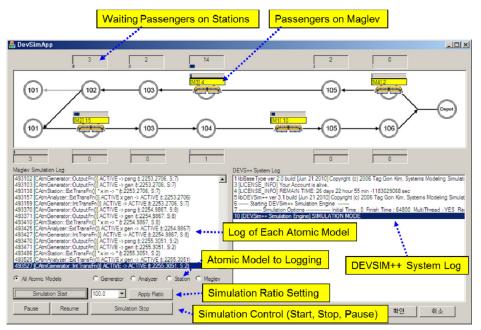

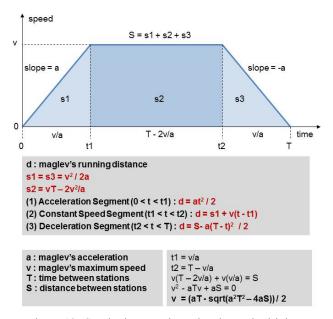Figure 11. GUI of the prototype simulation system.

Figure 12. Continuity equation related to train driving.

Figure 13. Time-based standard passenger generation rate.

Generator. CAtmAnalyzer also checks the simulation stop condition and, if needed, outputs a cease message (Stop) in order to stop the whole simulation process. The DEVS diagrams for these atomic models are shown in Figures 9 and 10, respectively.

4. Implementation and experiment

4.1 Prototype simulation system implementation

The object-oriented programming languages C++ [16] and DEVSim++ were used to develop a prototype simulation system that updates system information (i.e., state information) by order of event occurrence, and to carry out the simulation as a whole in line with the hierarchical scheduling algorithm. The GUI of the prototype simulation system implemented in this study is shown in Figure 11. This simulation system presents a wide array of information, both in graphics and in text. Data are graphically expressed at the top of the GUI to help users intuitively identify changes to the Maglev train's operation and passenger boarding/alighting. The box on the left list displays messages and log information related to boarding/alighting simulation, and the box on the right list provides log information for the DEVSim++ engine. User input buttons, check boxes, and the text box are at the bottom left of the GUI. They are used to perform simulation control such as the simulation ratio setting, simulation beginning, and simulation ending.

4.2 Train driving control in the ATO of the system

The ATO of the prototype simulation system should simulate continuous movement of the train. To realize this, we created a simplified continuous train driving model by referring to the DIA, which contains the train operation plan data including the distance between stations, standard driving time
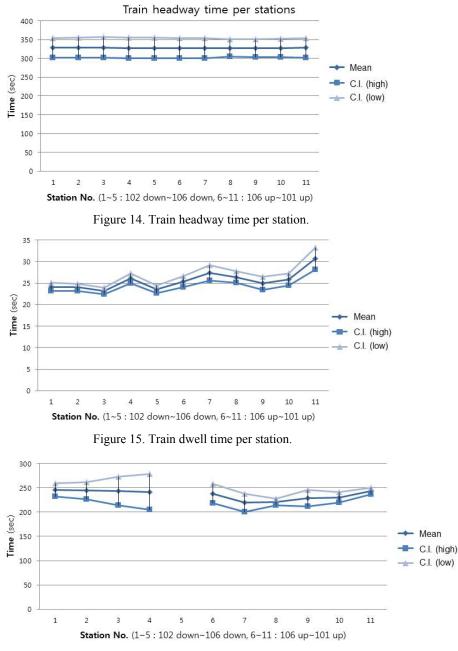
between stations, and maximum speed between stations. The simplified continuous train driving model repeats accelerated, decelerated, and constant velocity motion at the constant acceleration quantity. In a real situation, train driving motions are dynamic due to the gradients and curves of the railway. In this study, we focused on the passenger boarding/alighting simulation for each station, so it was reasonable to adopt a simplified driving model in order to acquire a certain event time. We defined the continuity equation of motion shown in Figure 12. The continuity equation calculates the driving distance between stations by time, and the position of the train at every simulation step.
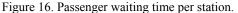
In addition to the driving performance of the train, it is very important to keep a marginal distance with the proceeding train in the railway control system. When a delay of the proceeding train occurs due to traffic waves, signal control should be applied to the following train to prevent an accident. This aftereffect is propagated to the subsequent following trains. Normal unmanned trains are controlled by a moving block system that controls the speeds of the trains by checking the distance from the proceeding train in real time. In this study, we implemented the moving block scheme by pausing the train's movement when the headway distance is shorter than the predefined marginal distance (1 km).

4.3 Simulation of traffic waves

The most important aspect of this study is to consider passenger fluctuation resulting from traffic waves for the Maglev transport simulation. For this, we analyzed the traffic impact assessment document, which contains daily traffic demand prediction data for the stations, and hourly passenger prediction data during the peak time zone. This document also includes traffic analysis results for surrounding streets. On this basis, we determined the peak time zone, quiet time zone, and normal time zone according to the level of crowdedness.

The standard passenger generation rate for each time zone was then determined using the aforementioned data, as shown in Figure 13. Peak and quiet time zone data were derived from the prediction data directly, and normal time zone data were determined by averaging the two peak data. During the simulation process, the passenger generation rate at each station was calculated randomly with the standard passenger

Figure 14. Train headway time per station.

Figure 15. Train dwell time per station.

Figure 16. Passenger waiting time per station.

generation rate data such that the passenger generation rate at each station represents a Poisson distribution [17]. The Poisson distribution is a discrete probability distribution that expresses the probability of a given number of events occurring in a fixed interval of time and/or space [18]. In addition, it is necessary to predict the alighting station per passengers for the train. Alighting rate at each station was designed to correspond to the standard passenger generation rate shown in Figure 13.

The boarding/alighting time of passengers is an important factor that affects the dwell time of the train. The time needed to open and close the doors is pre-defined. However, the boarding/alighting time per passenger is hard to predict. We

referred to experimental data from Seoul Subway Line 2 in South Korea [19], and defined the boarding mean time per person as 0.88 s and the alighting mean time as 0.76 s. Though the boarding/alighting time is usually affected by the crowdedness on the train, we did not consider this in order to simplify the input data required for the simulation. Since maintaining the standard dwell time at each station was specified by the current Maglev operation strategy, the train should dwell this time even if there are few moving passengers.

4.4 Experiment results

In order to evaluate normal train operation and examine

the service quality of the applicable line with respect to traffic waves, we determined the headway, dwell time, and passenger standby time based on the simulation results. The headway was calculated based on arrival/departure information by station, and is compared with the headway specified in the operation plan to verify the plan. The dwell time and passenger standby time were adjusted by the signal control when the number of passengers was too high or when the preceding train was delayed. We compared the dwell time and passenger standby time with the original schedule in the operation plan in order to quantify the inconvenience experienced by onboard passengers or standby passengers.

The train headway time, average dwell time, and waiting time per passenger at each station were analyzed based on the experiment results and are shown in Figures 14, 15, and 16, respectively. In the case of station 106, the down-way and up-way platforms were separated as different stations (station 5 and station 6, respectively).Only alighting passengers were present at station 5. Therefore, the passenger waiting time data at station number 5 is not represented in Figure 16. Simulation results show that headway stood at 5.45 min, constituting a slight delay relative to the time stated (i.e., 5 min) in the initial operation plan. This is presumably because the operation strategy specifies that the dwell time should be longer than the standard dwell time when there are many passengers, and that the standard dwell time (20 s) must be observed when the number of passengers is small. The average dwell time was simulated at 25.6 s because the average passenger boarding/alighting time exceeded the average dwell time as a result of the aforementioned operation strategy. The passenger standby time per station was estimated to be 3.9 min on average, with southbound tracks having a longer standby time than the northbound tracks overall. This is essentially because station 101 (the transportation center, where the northbound and southbound tracks cross each other) involves considerable traffic demands and often experiences delays, as passengers for both northbound and southbound trains board and disembark at the same time. Delay due to passenger congestion in station 101 also causes an increase of the standard deviation of passenger standby time on the southbound tracks. In addition, station 104 on the northbound tracks (station 8 in Figure 16) has a higher passenger generation rate than other stations and many passengers wait nearly for the average passenger standby time in this station. Because of this, the standard deviation of passenger standby time in this station is smaller than other stations. As a result, operation plan for the southbound tracks needs to be more carefully designed than the northbound tracks from the view point of the service quality.

Based on the simulation results, the proposed method can be used to review the operation planning and strategy of the Maglev. The simulation results showed that the service quality from the view point of time varies depending on stations but those variations are within acceptable limits.

5. Conclusions

We proposed a new DES-based train transport simulation technique to reflect the dynamic changes of passengers for the Maglev transit system, whose commercial application as a new means of transport is actively underway. We used a predesigned train operation plan and demand forecast data for each train station to design a discrete event-based modeling and simulation method for examining the train operation plan and strategy prior to actual operation. We also implemented and tested the system using DEVS formalism and the DEVSim++ simulation environment to verify the feasibility and usability of the proposed approach. System modeling and simulation methods proposed in this study can be applied not only to the Maglev, but also to other types of rail transportation that are operated by an unmanned automatic control system.

The passenger generation rate was estimated from daily traffic demand prediction data. However, this traffic demand data can be affected by various environmental factors. Therefore, for precise traffic prediction, simulation with real passenger statistical data should be performed in the future. The passenger boarding and alighting time was predicted based on experimental data from Seoul Subway line 2. In the real situation, boarding and alighting time is usually affected by the crowdedness, door position of a train, and passenger route at stations. Therefore, real operational data need to be gathered in order to enhance the quality of simulation. In addition, the time to open and close doors of a train and the intermediate dwell time for safety should be determined considering real train door performance and operation strategy.

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