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Movement and dwell time of MRT in SimMobility:

Technical Specifications

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Table of Contents

0 Document Control

0.1 Summary

This document contains the technical specifications for modelling the movement of MRTs in SimMobility. This includes the modelling of stations, movement, signalling systems, and train dwell time.

0.2 Document History

Version	Date	Author	Changes since last version
0.1	25-Jan-16	Kenneth Koh	First Draft

0.3 References

[1] Ravichandran, Harshavardhan. *Evaluating the robustness of crew schedules for rail transit systems*. Diss. Massachusetts Institute of Technology, 2013.

[2] Grube, Pablo, Felipe Núñez, and Aldo Cipriano. "An event-driven simulator for multi-line metro systems and its application to Santiago de Chile metropolitan rail network." *Simulation Modelling Practice and Theory* 19.1 (2011): 393-405.

[3] Nunez, Felipe, et al. "Simulating railway and metropolitan rail networks: from planning to on-line control." *Intelligent Transportation Systems Magazine, IEEE* 2.4 (2010): 18-30.

[4] Hill, R. John, and Louisa J. Bond. "Modelling moving-block railway signalling systems using discrete-event simulation." *Railroad Conference, 1995., Proceedings of the 1995 IEEE/ASME Joint*. IEEE, 1995.

[5] Cha, Moo Hyun, and Duhwan Mun. "Discrete event simulation of Maglev transport considering traffic waves." *Journal of Computational Design and Engineering* 1.4 (2014): 233-242.

[6] Lin, Tyh-ming, and Nigel HM Wilson. "Dwell time relationships for light rail systems." *Transportation Research Record* 1361 (1992).

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[8] (Besak, Lu, & Robinson, Movement and dwell time of buses in DynaMIT 2.0 and SimMobility: Technical Specifications, 2013)

[9] Nash, Andrew, and Daniel Huerlimann. "Railroad simulation using OpenTrack." *Computers in railways IX* (2004): 45-54.

[10] http://www.jbss.de/

[11] Sánchez-Martínez, Gabriel Eduardo. *Running time variability and resource allocation: a data-driven analysis of high-frequency bus operations*. Diss. Massachusetts Institute of Technology, 2012.

[12] http://paginas.fe.up.pt/~feliz/man/modeller.html

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0.4 Distribution

0.5 Quality Assurance

Step	Description	Undertaken By	Date	Remarks
1	Quality Review			

2	Project Manager			
3	Executive Review			

1 INTRODUCTION

The goal of SimMobility is to simulate a Public Transit system in detail. The current version of SimMobility simulates bus movement at both the microscopic and mesoscopic level, with several documents describing how this is achieved. For example, there are currently documents detailing the technical specifications and implementation of how bus movements and passenger demand are modelled in the SimMobility mid-term and short-term [8].

This technical specification will focus on how the movement of MRTs will be modelled. This includes movement between stations, behaviour at stations, signalling system effects, and modelling station dwell times. The MRT movement will be designed to mirror the philosophy of the Bus movement design whenever possible.

This paper is organized as follows: Section 2 provides a literature review of existing train simulators and methods, as well as a glossary of key terminology. Section 3 elaborates on the requirements of the SimMobility model and describes a “use case” of all key processes in a block of vehicle journeys. Section 4 presents an overview of the stages of MRT movement, while Sections 5 through 7 elaborate on the methods of modelling train movement, station behaviour, and the external service controller respectively. Finally, Section 8 elaborates on the implementation methods, such as the database structure and class structure, of the simulation. Section 9 then mentions points for further development and future improvement of the simulator.

2 Literature Review

Author
Comment [1]: Explain what the entire point of modelling MRT/rail is

This section provides a short literature review of modelling the movement of trains in a simulator. Section 2.1 discusses how MRT travel time can be disaggregated into various components, while Section 2.2 elaborates on this by briefly addressing methods of modelling dwell time. Section 2.3 evaluates the advantages and limitations of currently existing train simulators (both academic and commercial). Section 2.4 provides a glossary of key terms that will be used in this document.

2.1 Disaggregating MRT travel time into component parts

Author
Comment [2]: Talk about the important parts of the simulation

Train travel time can typically be disaggregated into two major components:

- **Drive Time:** Time that the train spends moving between stations.
- **Dwell Time:** Time that elapses between the door opening and door closing of a train sitting at a station.

A more comprehensive disaggregation of dwell time has been suggested in reference [5]:

- **Door-Operation Time:** Time spent opening and closing the train doors at a station.
- **Get-off time:** This is the total time that passengers spend alighting from the train.
- **Get-on time:** This is the total time that passengers spend boarding the train.
- **Idling Time:** This represents any additional time the train spends at a station.

However, most literature on dwell time such as [6] consider boarding and alighting to take place simultaneously; indeed, the delay resulting from the interaction of these two passenger streams is represented via a *congestion term* in the model. The door-operation time is also often ignored, as it typically represents a negligible portion of the overall dwell time.

2.2 Modelling dwell time

Author
Comment [3]: Move this to the dwell time section, not integrated

There are several approaches to modelling train dwell time, ranging in complexity.

The freeware railway simulator *JB BAHN* [10] adopts the simple approach of randomly and uniformly drawing from a pool of prospective dwell times. However, this approach lacks accuracy and is unlikely to mirror real-world conditions.

An improved approach is to draw dwell times from a calibrated distribution, based off historical data. This approach is used in various simulators such as [11]. However, this method by default assumes a largely stable demand; as a result, the resulting simulation can only be used for supply-side analysis.

The Maglev simulator in [5] utilizes historical data to calculate the mean boarding and alighting time *per passenger*, which is then multiplied by the total number of alighting and boarding passengers to obtain the dwell time. However, this model relies on the simplifying assumption that dwell time scales linearly with passengers, and ignores congestion-related effects, thus sacrificing a degree of accuracy.

In this proposed Train Simulator, dwell time is calculated via the method proposed in [6] and depends on train occupancy and the number of boarding and alighting passengers. Although calibrating the formula takes a significant amount of time, it results in the highest degree of accuracy in dwell times across fluctuating demand. For more information, the user is recommended to refer to [7].

--incomplete (mention automated train dwell time formulae)--

2.3 Simulating public transport

This section describes how trains have been modelled in existing software simulations. To begin with, the characteristics of different categories of simulators are explained and compared. A series of existing train simulations are then reviewed.

2.3.1 Macroscopic, Mesoscopic, and Microscopic models

There are three types of commonly used simulation models, which are briefly described here:

- **Microscopic:** Each individual entity in the simulation is explicitly modelled. The movement of each entity is determined solely from information available to the individual entity. In the context of train simulations, this means that each train will be modelled explicitly. Dwell time at stations is determined by passenger behaviour models that replicate the decisions made by individual passengers when boarding or alighting. Although these models are highly accurate, they involve significant computation costs.

- **Macroscopic:** Entities are aggregated together and not modelled individually. In the context of train simulations, dwell time at stations is determined by a function of the number of boarding passengers, alighting passengers, and overall crowdedness of the train. These models tend to be less accurate than microscopic models but are often orders of magnitude quicker to run.

- **Mesoscopic:** Entities are implemented using both aggregated and disaggregated models. In the context of train simulations, and especially this simulation, demand will be modelled at a disaggregate level (i.e. individual passengers are modelled). However, train drive time and dwell time will be modelled at the macroscopic level.

The reasons for modelling at different levels of detail are:

- **Computational performance:** macroscopic models are often orders of magnitude quicker than microscopic models.
- **Accuracy:** Microscopic models tend to provide more accurate simulations than macroscopic models.
- **Data availability:** Macroscopic models tend to require less detailed information about the network.

Ultimately, the decision on what level to model at is primarily a decision between accuracy and computational speed. It is therefore necessary to know how accurate the results need to be when choosing how to model the various entities of interest. Various train simulation software have been implemented using microscopic, mesoscopic, and macroscopic models. Those relevant to this simulation are elaborated upon below.

2.3.2 Summary of alternative simulators

Much work has gone into investigating train scheduling and supply problems, and as a result many train simulators have been developed by both academic and commercial parties. Tools such as Bahn [10] and MetroModSim [12] have been developed by independent parties to provide primarily *visual* representations of proposed train networks. OpenTrack [5], a microscopic synchronous railway simulator, provides a comprehensive model of train movement across long distances; however, it does not focus on demand-side effects such as dwell time. Grube et al [2] and Sánchez-Martínez et al [11] both developed discrete event-based simulators to study train scheduling that included the effects of passenger demand, based off historical data. However, the former model made the simplifying assumption of trains having constant speed, while the latter model utilized historical running time data to model train movement. A train operation model should utilize a continuous speed profile and consider acceleration, in order to increase accuracy and realism. Cha et al [5] developed a time-based simulation model for Maglev trains, but used a simplified dwell time model that ignored congestion effects.

2.4 Glossary of terminology

This section defines a common glossary that will be used throughout the technical specification documents. This is particularly necessary when modelling Public Transport as certain words can mean different things to different people – in particular the words “route” and “trip”. The glossary is in alphabetical order.

Word	Description

Word	Description
Access Walk	This refers to the movement of a person from their origin point to the first stopping point in the trip.
Direction	Refers to which way a line is running in. For example, NS Line: Direction 1: Harbourfront → Punggol, Direction 2: Punggol → Harbourfront
Egress Walk	This refers to the movement of a person from their last stopping point in the trip to their final destination.
Line	A service which is known to passengers by a common number or name. For example the “NEL” is a line between Harbourfront and Punggol operated by a train.
MRT	Mass Rapid Transit—the name of Singapore’s urban rail network.
Operational Day	This refers to a day used in a schedule. An operational day allows for the fact that vehicle journeys on a line can straddle two calendar days or even start after midnight. A 29 hour day is typically used with timings after midnight starting with 24. A typical Operational Day runs from around 02:00 to 05:00 the next calendar day, i.e. 02:00 to 29:00.
Path	Describes the sequence of access walk, rides, transfer walks, and egress walks that a passenger took on a trip.
Pattern	Describes the exact sequence of stopping points that a PT vehicle takes on a given vehicle journey. Typically a line has two patterns, one in each direction. If a line has short working vehicle journeys then there will be more than one pattern for the line-direction.
Ride	Describes a single movement on a single vehicle carried out as part of a

Word	Description
	Trip.
Stopping Point	Describes a location where a passenger may board or alight from a Public Transport vehicle. In practice this is typically a station platform.
Transfer Walk	Describes the movement of a passenger between different vehicles in a trip.
Trip (PT Trip)	Describes the movement of a person between an origin point O, and a destination point D.
Vehicle Journey	An instance of the service on a given line provided between a starting stopping point A and end stopping point B.

Table 1 – Glossary of terminology used in the modeling of Public Transport

3 Requirements for modelling MRT movement

It is important to review the requirements for modelling the movement of MRT. This chapter reviews these requirements. Section 3.1 summarizes all output data required from the simulator, while Sections 3.2 and 3.3 briefly address any additional requirements. Lastly, Section 3.5 provides a “use case” for modelling an in-service MRT train. This provides a reference to ensure the thoroughness of the developed train simulator.

3.1 Requirements on data to be measured

Table 2 below summarizes all the output data required from both the supply and demand train simulators. Note that the Short-Term and Mid-Term simulators must share a common output file for each entity. However, some attributes will only be available in the Short-Term simulator; these will be indicated by an asterisk. The “model used” attribute indicates whether the data originated from the Short-Term or Mid-Term simulator.

No	Name	Description

01	Train-Station Interactions	Every time a train departs from a station, a record with the following attributes must be provided: • Train Number • Trip ID • Line ID • Station Number • Platform Number • Arrival time at station • Departure time from station • List of passengers on board • List of passengers that boarded • List of passengers that alighted • List of passengers that failed to board • Dwell time • Model used
02	Train Status	During each time-step, each train should update and record its current location. The following attributes should be provided: • Train Number • Current time • Location of Vehicle • Trip ID • Line ID • Current speed • List of passengers on board* (not output, keep in memory) • Model used

03	Platform Status	During each time-step, each platform should update and record its current status. The following attributes should be provided: • Station Number • Platform Number • Current time • List of passengers waiting at the platform • Model used
11	PT Trip	A "PT Trip" describes a series of rides made by a passenger travelling between a given origin and destination. The following attributes should be recorded as the output for every completed PT Trip: • Passenger ID • Time of trip start • Time of trip end • Origin location • Destination location • List of completed rides, access, egress and transfer walks
12	Ride	For each completed Ride, the following data will be recorded as output: • Passenger ID • PT Trip ID • Time of boarding • Time of alighting • Waiting time (at each station)

		• Start station • End station • Train Number • Line ID
13	Walk: Access, Egress, Transfer	For each completed transfer walk the following data will be recorded as output: • Passenger ID • PT Trip ID • Type of walk: access, egress, or transfer • Timestamp departed start stop point • Timestamp arrived end stop point • Stop Point start: can be null for access walks • Stop Point end: can be null for egress walks • Location start: can be null for egress or transfer walks • Location end: can be null for access or transfer walks
21	Location in local format	The system must be able to provide the location of a train in the local coordinate system.
22	Location in WGS84 format	The system must be able to provide the location of a train in WGS84 format.
23	Location of vehicle: Linear Reference System	The system must be able to provide the location of a train using a linear referencing system. Typically this will include the following attributes: • Block Number • Distance from start of block
31	Format of data	All records stated above shall be stored as UTF-8 files. These files can be compressed as required.

3.2 Other general requirements

A list of other requirements for the modelling of Public Transport is given in Table 2.

No	Name	Description
301	Calibration	
302	Accuracy	
303	Computationally quick	
304	Data availability	
305	Common Mode design	A common design for modelling MRT and buses should be used where possible.

Table 2 – Other requirements for modeling Public Transport in DynaMIT and SimMobility

3.3 MRT specific requirements

A list of MRT specific requirements for the modelling of Public Transport is given in Table 3.

No	Name	Description
401	Competition for shared track	The system must be able to account for multiple trains competing for the same track, such as: • Cross-roads • Two trains competing for one platform
402	Station types	The system must be able to account for different types of stations, such as:

		• Stations which allow trains to U-turn • Stations with multiple tracks serving the same Line • Stations with multiple Lines sharing the same track
403	Train types	The system must be able to support different types of trains varying in: • Length • Capacity

Table 3 – MRT specific requirements for modeling Public Transport in SimMobility

3.4 Use case of modelling an MRT service

As a validation stage in eliciting requirements it is often useful to produce a flow diagram indicating the key processes in the movement of a train in the proposed simulation. This flow diagram should indicate all possible processes that might occur, and should be catered for when designing the simulation. Such a diagram was produced and is shown in Figure 1. There are two main "actors":

- **Controller:** An external manager who handles the operation of the train line.
- **Vehicle:** The transport vehicle in question (in this case, a MRT train)

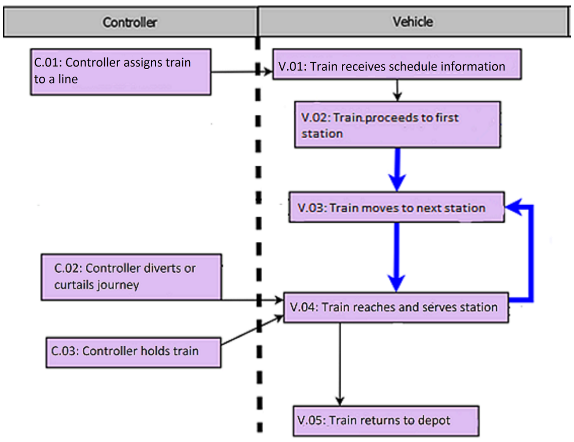


Figure 1 – Flow diagram indicating the movement of a train in a block of trips

Each process is described briefly in Table 6. The primary flow refers to processes which occur during typical train operation. The “alternative flows” refer to processes which may occur under exceptional circumstances.

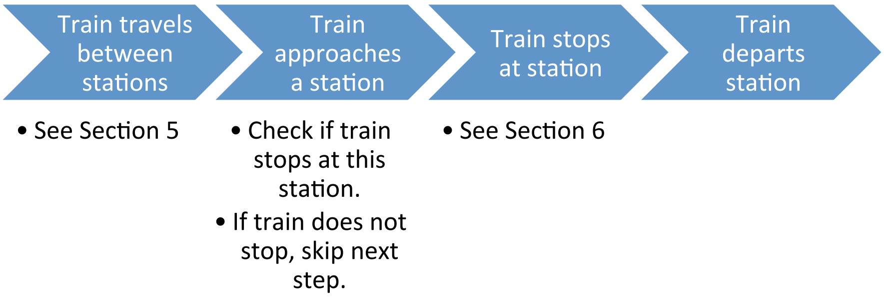
Name	Description
PRIMARY FLOW	
C.01: Controller assigns train to a line	The controller assigns a currently out-of-service train to a line. This assignment may correspond to the line-specific schedules (a fixed input to the simulation), or may be an exceptional out-of-schedule decision.
V.01: Train receives schedule information	This includes which line the train will service, its departure time from first station, return time to depot, which depot to return to, etc.
V.02: Train proceeds to first station	The train moves to the first station of its journey. Note that this could be the end stations of the line, or the closest station to the depot, or any other station as determined by V.01.
V.03: Train moves to next station	The train moves from one station to the next along the track corresponding to its line. Trains will naturally loop at end stations; therefore, there is always a “next station” in

	the line.
V.04: Train reaches and serves station	The train will stop at all scheduled stations, regardless of whether passengers actually with to board or alight at these stations.
V.05: Train returns to depot	Once the "return time" in V.01 has passed, the train returns to its scheduled depot. *Note that depending on schedule information, the train may or may not serve all stations between its current position and the depot.*
ALTERNATIVE FLOWS	
C.02: Controller diverts or curtails journey	Depending on the system state, the controller may decide to prematurely return a train to the depot. Alternatively, it may divert the train to another line, or force the train to prematurely U-turn in order to fix delays.
C.03: Controller holds train	The controller may choose to force a train to remain stationary at a station. This may be done in headway control strategies.

4 Overview of modelling movement of MRT

Section 4 provides a brief overview of the steps involved in modelling train movement. Sections 5 – 7 will further elaborate on these steps.

4.1 Stages of MRT movement



5 MODELLING TRAIN MOVEMENT

This section describes in detail the first stage of Figure 1: train movement between stations.

5.1 Train movement

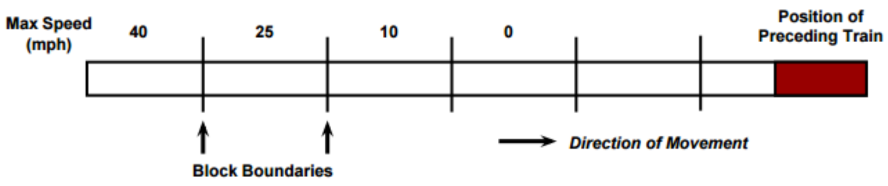
Train speeds can be arbitrarily set by an external service controller. However, if no instructions are given, then the simulator must be able to simulate two types of movement for the user to choose from: Fixed Block, or Moving Block. For a more in-depth discussion of signaling principles, the user is recommended to refer to [4].

Note that in both cases, reference is always taken from the front of the train.

5.1.1 Fixed block

In fixed-block signalling, the track is divided into sections called blocks. Each block has a variable speed limit, as well as fixed values of train deceleration that depend on the specific track geometry that the block belongs to.

Whenever a train occupies a block, the speed limit for that block and a certain number of blocks preceding it (the *safe operating distance*) is set to zero. Blocks before those have gradually decreasing speed limits that correspond to the values of train deceleration. This is shown graphically in the figure below:



Depending on the type of signalling system used, each block can have anywhere between 3 to more than 10 different speed limit settings, known as “phases”.

Finally, it should also be noted that there are 2 variations of the fixed-block signalling system. In the first variation, the speed limit of the approaching block is instantaneously transmitted to the train (thus allowing the driver to act on it immediately, for instance by slowing down beforehand); in the second variation, this information is only transmitted at the block boundaries, resulting in a “lagged” response by the train to changes in the network. This simulation uses the first variation by default.

5.1.2 Moving block

In moving-block signalling, trains are continuously in contact with a central computer. Therefore, any one train always knows the speed and position of all the trains in the system as well as its own deceleration rate.

A train operating under moving-block signalling will continuously calculate the distance to the point ahead where it must come to a stop (the next station, or the end of next train + safe operating distance), and continuously adjust its speed such that it will be able to decelerate fully over this distance.

5.2 Design considerations

Moving-block signalling systems are generally easier to implement in simulation models as they require little input data. In contrast, modelling fixed-block signalling systems requires knowledge of the block lengths along the track, the number of phases a block has, and the speed limits that correspond to these phases. The specific variation of fixed-block signalling system must also be known to ensure accuracy in the model.

However, fixed-block signalling systems correspond to the vast majority of signalling systems used in urban metro systems worldwide, although this is changing as cities begin to modernize their metro networks. Nevertheless, for this reason it is still important for this simulator to be able to model fixed-block signalling systems.

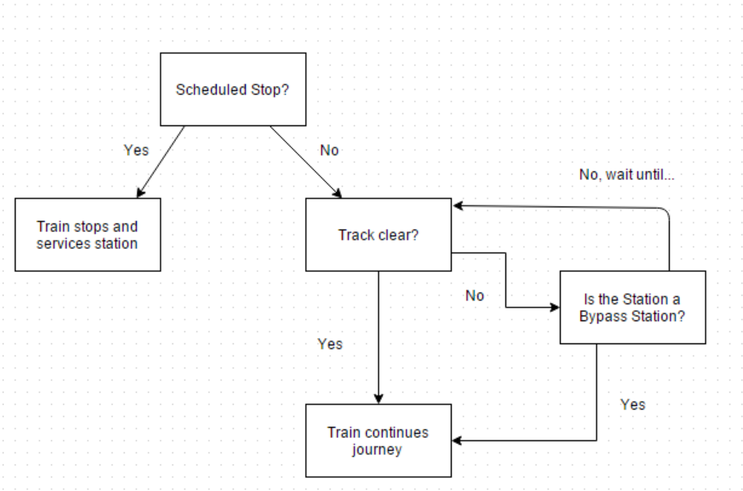
6 MODELLING STATION BEHAVIOUR

This section describes in detail the second, third, and fourth stages of Figure 1: Station Behaviour. Note that, as in Section 5, all subsequently described behaviour can be overridden or arbitrarily altered by the external service controller.

6.1 Approaching the Station

A train will stop at all stations listed on its schedule.

If a train is *not* scheduled to stop at a station, but the track is occupied, the train checks if the station is a "bypass" station (see Section 8.2.1). If so, the train continues on its journey; if not, the train obeys signalling logic and waits behind the preceding train until it is safe to move. This decision logic is shown in the figure below:



6.2 Station Behaviour

Upon arriving at a station, a train will perform the following actions in sequential order.

Firstly, by referencing the schedule, it determines its departure behaviour—whether it is continuing to the next station along the line, heading to the depot, performing a “U-turn” (effectively reversing and servicing the line headed in the opposite direction), and so on.

The train and station occupancies and passenger lists are then updated according to the Origin-Destination matrix of passengers at the station.

This change in occupancy is then used to calculate dwell times. The methods used are further elaborated on in Sections 6.2.1 and 6.2.2.

Any additional delays are then calculated. These delays could occur due to the train’s intended behaviour (for example, if the train plans to “U-turn” or uncouple cars), schedule (if the train plans to switch to another line), or external factors (a change in train drivers).

Finally, the train departs after waiting for a period given by the sum of dwell time and additional delays.

6.2.1 Dwell Times (Manually Operated Trains)

Dwell time is defined as the time that elapses between the door opening and door closing of a train sitting at a station and is primarily devoted to the loading and unloading of the train. Dwell time is affected by both *system specific* factors, namely passenger loads and behaviour, and *external* factors such as operating practices, climate, and so on [13]. However, given that the latter is hard to quantitatively measure, they are usually dealt with via an error term.

A simple linear model of the dwell time DT is as follows:

$$DT = \beta_0 + \beta_1 Boarding + \beta_2 Alighting + \beta_3 Congestion$$

where

Boarding = Total number of boarding passengers,

Alighting = Total number of alighting passengers,

Congestion = A term that reflects the overall congestion level of the train,

$\beta_{0,1,2,3}$ = Parameters to be determined.

It has been shown in [6] that in non-congested situations, the *Congestion* term can be ignored with minimal impact on the accuracy of the predicted dwell time.

However, in congested situations, the *Congestion* term should reflect one or more of the following interactions, between:

1) Passengers staying on-board (through-standees) and alighting passengers;
2) Through-standees and boarding passengers;
3) Alighting and boarding passengers;
4) Interference within alighting passengers as their number increases, and
5) Interference within boarding passengers as their number increases.

Therefore, the exact composition of the Congestion term will vary from system to system or indeed even from rail line to rail line, and can only be determined from an understanding of existing conditions and an analysis of which model best fits the available empirical data.

6.2.2 Dwell Times (Automatically Operated Trains)

To be completed when information is obtained

6.3 Departing the Station

When a train departs the station, any departure behaviour determined in Section 6.2 immediately takes effect. For example, in this model, a North-bound train that “U-turns” at a station simply departs the station as a South-bound train. The actual “U-turn” effect is not explicitly modelled in the simulation.

7 THE EXTERNAL SERVICE CONTROLLER

In the daily operations of a rail line, train service often deviates from schedule due to changing circumstances such as variability in passenger demand, driver behaviour, or other unforeseen operating conditions. If these deviations are not corrected, they tend to increase in magnitude, rendering schedule adherence difficult. As such, every rail line is typically managed by a Service Controller, which modifies the train operations in real-time both proactively and reactively in order to ensure the system is able to continue functioning.

In this simulation, the Service Controller is represented by an externally written program that interacts with the simulation and uses (if…then) logic to modify train behaviour accordingly.

The following is a (non-exhaustive) reference list of common actions taken by Service Controllers to help rectify train disruptions:

Action	Description
Short-Turning	A train "U-turn" before the stop at the end of the line, thus helping it get back on schedule (if it was originally late)
Train Withdrawal/Trip Cancellation	Cancels part of (or the entire) trip, if running this trip would further increase delays in the system.
Holding at Stations	Holds a train past its actual required dwell time at a station. A form of headway control.
Expressing	A train skips stops to compensate for being behind schedule.
Extension	A train serves a station it was originally not intending to serve
Adding Service	An originally unscheduled train enters service.
Junction Priority	Gives a train priority at all junctions or shared track.

8 Implementation

8.1 Introduction

The North-East Line (NEL), colloquially referred to as the "Purple Line", was chosen as the test case for the proposed MRT simulator. This was done for a few reasons:

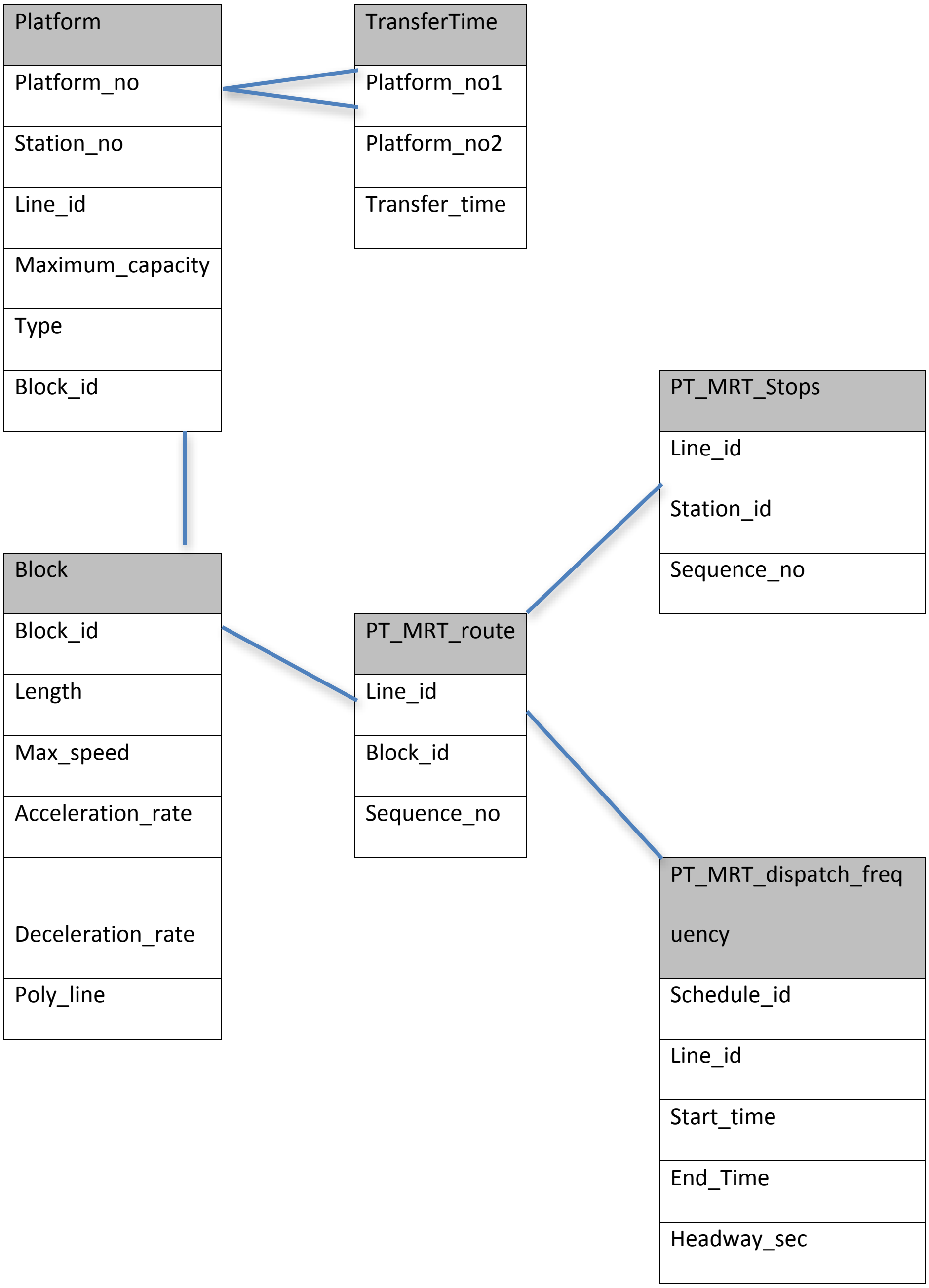
1) The NEL is fully automated. Therefore, dwell times can be obtained directly from a formula, which simplifies the model;
2) The NEL travels in a generally straight line with minimal curvature, thus reducing the complexity of the track infrastructure;
3) The NEL utilizes a moving-block signaling system and hence accurate block data is not required for an accurate model;
4) The NEL exists independently from the other rail lines in Singapore—there is no competition for shared track with trains from external lines.

The full range of data used in the test case, obtained with thanks from Singapore's Land Transport Agency (and whoever else helped, etc etc), is shown in the table below:

Singapore North-East (Purple) Line – Operated by SBS	
Number of In-Service Trains	Infinite
Passenger Capacity per Train	1920
Train Length	142m
Acceleration, Deceleration, Max Speed	Accel/Decel: 1.1ms^{-2}
Key Stations	None
Scheduling Logic	FIFO
Safe Operating Distance/Headway	120 seconds
Dwell Time Logic	Uniform 25-60 seconds

8.2 Database Diagrams

8.2.1 Overall MRT Network



Name	Description
BLOCK	
Block_id	An identifier. A block represents a section of track between stations. Each platform is also considered a stand-alone block.
Length	The length of the block.
Max_speed	This limits how fast trains can travel when on this particular block.
Acceleration_rate	This corresponds to gradient, curvature, and other infrastructural elements of the block.
Deceleration_rate	See *Acceleration_rate*.
Poly_line	Represents curvature of the block.
PLATFORM	
Platform_no	An identifier. More than 1 platform can be linked to the same Line_id.
Station_no	An identifier. Links each platform to a parent station.
Line_id	An identifier. Note that each Line_id corresponds to a specific direction (e.g. North South Line heading North)
Maximum_capacity	Once this passenger capacity is exceeded, the platform is considered full and will not accept any new passengers.
Type	Defines the characteristics of the platform: • End-of-line: Last platform in a

	direction; all trains terminate or U-turn here. • U-turn: Trains have the *ability* (but are not required) to U-turn here. • Pre-depot: This platform is adjacent to a depot.
Block_id	The block that the platform corresponds to.
TRANSFERTIME	
Platform_no1	The identifier of the first platform.
Platform_no2	The identifier of the second platform.
Transfer_time	The time taken for a passenger to walk from the first platform to the second platform.

8.2.2 MRT scheduling

See “PT_MRT_dispatch_frequency” in Section 8.2.1.

Name	Description
Schedule_id	An identifier.
Line_id	The line that this schedule corresponds to.
Start_time	Start time
End_time	End time
Headway_sec	The headway (in seconds) at which trains depart from the specified control platform.
Platform_no	The control platform.

8.2.3 MRT Route

See “PT_MRT_route” and “PT_MRT_Stops” in Section 8.2.1.

Name	Description
Line_id	An identifier.
Block_id (or Station_id)	A list of all blocks (or stations) that form the train line.
Sequence_no	The order in which these blocks (or stations) occur in the train line.

8.2.4 Rolling Stock

TrainVehicle
Capacity
Length

TRAINVEHICLE	
Capacity	The passenger capacity of a train.
Length	The length of the train.

8.3 Differences between Mid-Term and Short-Term

8.3.1 Train Movement

Due to the comparatively fewer amount of entities in the Train Simulator as compared to the Bus Simulator, train movement can be modeled at the microscopic level in both the Mid-Term as well as the Short-Term simulators (see Section 5). As a result, it is important to keep the time-step between the updating of variables small in order to preserve accuracy. Typically, commercial microscopic simulators use a time-step of 1 second [9], while the Bus

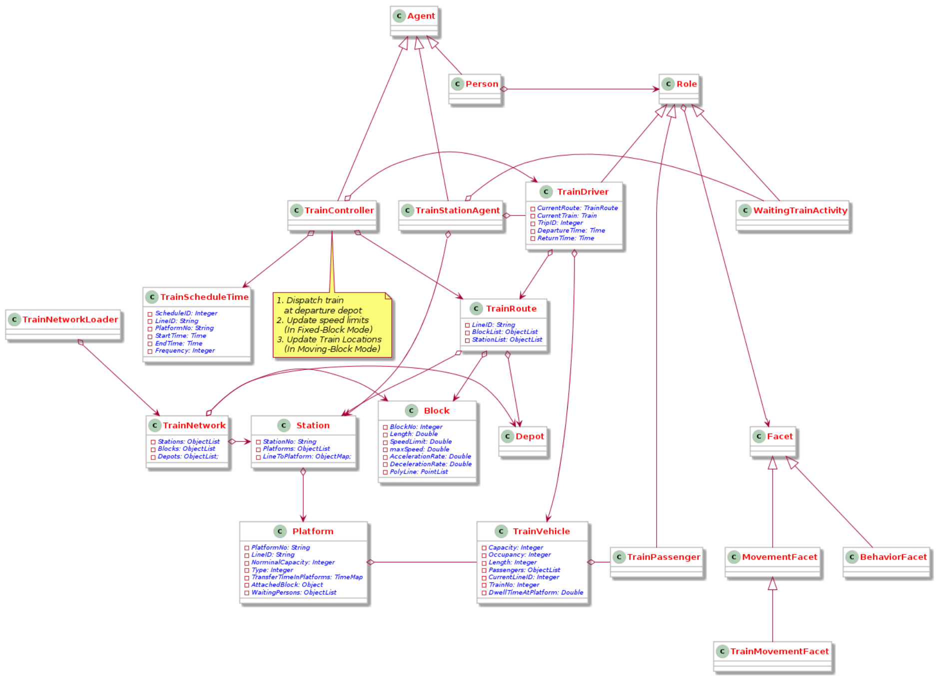
Simulator uses a time-step of 5 seconds [8]. Therefore, for the Train Simulator, we suggest that the Short-Term use a 1-second time step and the Mid-Term a 5-second time step.

8.3.2 Dwell Time

In the Short-Term, the dwell time is determined from the simulation itself as the movement of individual passengers onto and off the train is explicitly modeled. However, in the Mid-Term, dwell time is determined from a predefined formula. The number of boarding and alighting passengers is calculated at the instant when the train pulls into the station. As a result, in the Mid-Term simulation only passengers already waiting at the station when the train arrives are “allowed” to board the train. However, in the Short-Term, “late arrivals” are able to board the train as well. (Might need to elaborate/modify this when information on automated dwell times is known)

8.4 Class Diagram

The Class Diagram of Train Behavior In Medium-Term



9 APPENDIX 1: REMAINING TASKS FOR THE FUTURE IMPLEMENTATION

Appendix 1 is incomplete; ignore what is below and move on to Appendix 2

We are currently developing a comprehensive supply-side MRT simulator for Singapore. By modelling the movement and interaction of trains with each other, we hope to be able to identify potential bottlenecks and investigate the effects of changes (for example, the introduction of new trains with increased capacities) on the overall performance of the system.

To this end, we require comprehensive data about the current MRT system in Singapore, in order to ensure the accuracy of the simulation. The data we require includes:

1) **Number of in-service trains for each line:** that is, the number of trains that can be called into service at any time, broken down by the number of train types (e.g. 50x C151A, 20x C151B) per line;
2) **Passenger capacity of each train:** broken down into capacity per train type;
3) **Length of each train:** broken down into length per train type;
4) **Key stations per line:** that is, stations where "special effects" (such as those with more than 2 platforms, with bypass tracks, or where trains can switch tracks and reverse direction) can occur
5) **Scheduling logic:** Please explain the train movement logic - when trains leave the depot, do they have a scheduled time at which they are supposed to return? Or are trains kept in service until a decision is made to return them to the depot? How is this decision made - what factors influence it?
6) **Signalling for LRTs:** Do CCK/Sengkang/Punggol LRTs use a fixed-block system? What is the block length?
7) **Safe Operating Headway:** What is the safe operating headway (the additional separation distance after allowing for braking distance) used in Singapore for each line?
8) **Dwell Time:** How are dwell times (the time a train spends waiting at a station) determined for trains (especially driverless trains) in Singapore?

10 Appendix 2: Train Movement Equations

In order to simplify the model, we assume that trains travel in regions of constant acceleration, constant speed, and constant deceleration. This method, as demonstrated by Kraft in [14], results in a fairly close approximation of the projected train trajectory and allows straightforward kinematic equations to be used in the model. This is also the method utilized in [4] and [5].

The kinematic equations that we will use are as follows:

1) $v^2 = u^2 + 2as$
2) $s = ut + \frac{1}{2}at^2$
3) $v = u + at$

Where *u* is the initial velocity, *v* is the final velocity, *a* represents acceleration, *t* the time, and *s* the distance between two points.

10.1 Moving Block

Start of Time-Step N

At every time-step, every train in the system reports its speed *u*, position *p*, acceleration rate *a* and deceleration rate *d* (this information is obtained from the block it is currently on). The distance between the front of the train and the end of the train in front of it *s** is calculated. Finally, the effective distance *s* is calculated by subtracting the safe operating distance (as determined by the operating agency) from the actual distance *s**.

We then obtain the theoretical speed limit L_t for the train (deceleration is positive):

$$L_t = \sqrt{2ds}$$

We then compare L_t to the predefined system speed limit L_s and we take the actual speed limit L as the minimum of the two:

$$L = \min(L_t, L_s)$$

If the current speed of the train $u > L$, the train begins to decelerate until it is travelling at L; if $u < L$, the train begins to accelerate until it is travelling at L.

Safe Operating Headway vs. Safe Operating Distance

Instead of defining a safe operating distance, some operating agencies instead choose to define a safe operating headway—that is, a minimum *time* t_{safety} that must separate two trains. In this case, we assume a safe operating distance of 0, i.e. $s^* = s$.

We then calculate a second theoretical speed limit L_{t2}:

$$L_{t2} = \frac{s}{t_{safety}}$$

That is, the speed at which the distance that the train would cover in the safe operating headway equals the distance to the train in front of it.

The actual speed limit is now the minimum of the three values:

$$L = \min(L_t, L_{t2}, L_s)$$

Similarly, if the current speed of the train *u* > *L*, the train begins to decelerate until it is travelling at *L*; if *u* < *L*, the train begins to accelerate until it is travelling at *L*.

Updating of Variables for Time-Step N+1

Let the duration between time-steps be *t*. In that case, for time-step N+1, the train's variables are updated as follows:

Firstly, we obtain the theoretical final velocity V_t of the train:

$$V_t = u + at \ (accelerating)$$

$$V_t = u - dt \ (decelerating)$$

We find the actual final velocity, *V*, by comparing with the speed limit of the first time-step, *L*:

$$V = \min(V_t, L) \ \ if \ accelerating$$

$$V = \max(V_t, L) \ \ if \ decelerating$$

This final velocity *V* is the new train speed for time-step N+1.

The effective acceleration *e* is thus:

$$e = \frac{V - u}{t}$$

Note that *e* can be positive or negative.

We then calculate the distance, *x*, travelled by the train during this time-step:

$$x = ut + \frac{1}{2}et^2$$

Finally, we update the new train position for time-step N+1 by adding the distance travelled by the train to its original position:

$$p_{time-step\ N+1} = p_{time-step\ N} + x$$

10.2 Fixed Block

Start of Time-Step N

At every time-step, every block in the system reports whether it is occupied (that is, whether there is a train currently running on it) or not. The speed limit L_k of an occupied block k is set to zero. The speed limit of a certain number of unoccupied blocks—corresponding to the Safe Operating Distance (rounded up)—prior to the occupied blocks is also set to zero. Finally, all blocks immediately after unoccupied train stations also have L_k set to zero.

The theoretical speed limit $L_{k,t}$ is then calculated for each block k with a non-zero speed limit. L_{k+1} refers to the speed limit of the block after block k in the direction of travel, d_k the deceleration rate of trains in block k (taken as positive), and s_k the length of block k.

$$L_{k,t} = \sqrt{L_{k+1}^2 + 2ds_k}$$

We then compare $L_{k,t}$ to the predefined system speed limit L_s and we take the actual speed limit of block k, L_k as the minimum of the two:

$$L_k = \min{(L_{k,t}, L_s)}$$

This speed limit is then rounded off to the nearest corresponding phase (speed setting).

if the current speed of the train on block k $u_k > L_{k+1}$, the speed limit of the *next* block, the train begins to decelerate until it is travelling at L_{k+1}; if $u_k < L_{k+1}$, the train begins to accelerate until it is travelling at L_{k+1}.

Safe Operating Headway vs. Safe Operating Distance

Instead of defining a safe operating distance, some operating agencies instead choose to define a safe operating headway—that is, a minimum *time* t_{safety} that must separate two trains. In this case, we assume a safe operating distance of 0; however, all occupied blocks remain "occupied" for a period t_{safety} after the train is no longer physically on the block.

Updating of Variables for Time-Step N+1

This is done in an identical manner to the moving block system (see above). Note that the block occupancies are also updated.