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A Simulation Model of Group Rapid Transit System

by
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Abstract

Group Rapid Transit (GRT) is a new idea of public transport using small automated railed vehicles to provide shared ride for grouped passengers. However, only few systems have been proposed in the real world with lack of materials supporting the idea. Based on hardware model, computer simulations and mathematical calculations, the theoretical behaviors and system characteristics of the GRT, and how it can contribute to the future development of intelligent transportation system, are investigated. The author found that the GRT outweighs the other existing systems by higher flexibility, efficiency and better energy utilization in fulfilling both peak and off-peak capacity, with improved ridership experience on access time and safety. In a future smart city, public transport can be completely detached from the private transport with the wide deployment of GRT.

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1.Introduction

Group Rapid Transit (GRT) is a new form of collective public transport using small driverless automated train vehicles to provide shared ride for grouped passengers. With a sufficiently extensive network up to city-wide scale, the GRT is expected to provide a more efficient, time-saving travels to passengers with the effective use of automation. A successful implementation of GRT is expected to eventually replace the conventional transits, such as buses, in a future smart city.



Fig 1.1 An art work imagining the future transportation system

1.1 The Group Rapid Transit

Group Rapid Transit (GRT) is a fully automated, driverless, grade-separated transit system in which vehicles operate on a network of specially built guideways.

GRT vehicles are sized for small group travel, typically carrying 20 to 40 passengers per vehicle. The service is demand-responsive - the vehicles are called by passengers when needed, making the operation like a horizontal elevator. The vehicle will arrive and then go directly to the selected destination unless called by other users to pick up along the way [1]. Scheduled services are also possible in resolving high travel demand in peak hours.

Guideways are arranged in a network topology; with all stations located on sidings, and with frequent merge/diverge points. With a sufficiently extensive network, passengers are able to travel citywide without shifting to other transport modes. The GRT can take relatively direct routes to their destinations without leaving the vehicle.

The high flexibility of the GRT is afforded under the control of full automation. The control system facilitates high degree of accuracy and vehicle coordination. Together with the exclusive right-of-way, the GRT system can offer a high frequency service while being able to maintain schedule in a safe environment.



Fig 1.2 The Morgantown Group Rapid Transit, West Virginia, the United States

1.2 The In-vehicle Interchange System

The in-vehicle interchange is a new idea of transportation management strategy. Passengers interchange between vehicles directly without using any physical medium, such as stations or platforms. Time loss due to cross-platform interchange can then be eliminated. This strategy is in the theoretical stage and no real implementation has been proposed yet.

In operation, vehicles from different routes are going to couple with each other, and passengers move among these two or more vehicles. After the interchange movements, vehicles separate and continue their journey of their own routes. It is expected that the use of on-vehicle interchange can facilitate shortened total travel time and reduced passenger delay, but the system requires substantial signal coordination and schedule management.

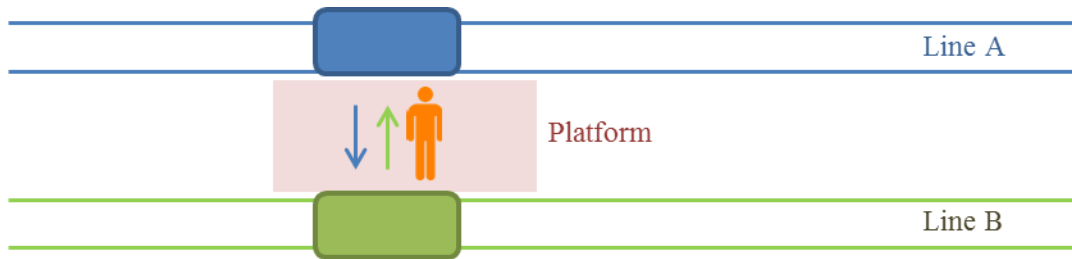


Fig 1.3 Cross-platform interchange

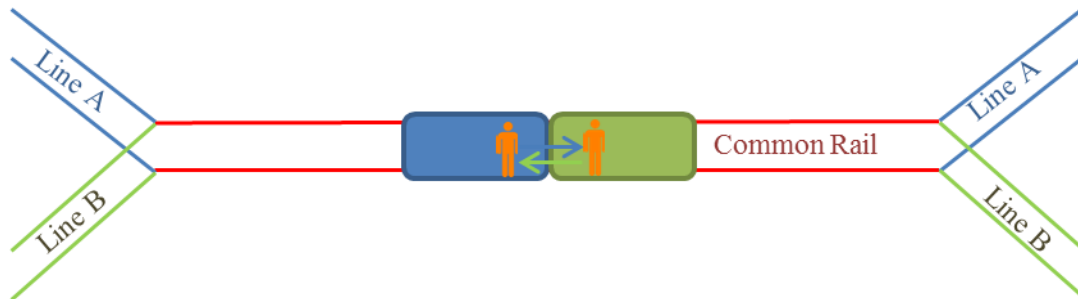


Fig 1.4 In-vehicle interchange

According to the research from University of Leeds [2], interchange time plays an important role in influencing the efficiency and total convenience of a railway system. Statistics shows interchange time forms around 20-25% of total travel time per trip, and the effective removal of interchange can increase demand by 22%. With the use of in-vehicle interchange, the interchange time can greatly be reduced as passengers do not need to cross the platform. Moreover, passenger movements occur between compartments without putting the train into total stop. The duration originally parking alongside the platform is eliminated.

Lecture notes from CSE40407 Design of Transport Infrastructure [3] can prove the theoretical effectiveness of in-vehicle interchange strategy. It is stated that acceleration and deceleration of train can influence the headway thus the total travel time spent in a railway system. In addition, shorter passenger boarding/alighting time can make the system more “productive”. It is achieved as passenger queueing and consolidation before entering the target train is not likely.

Another concern about cross-platform interchange is the poor arrangement of cross-flows of passengers. Cross-flow means passengers walking along one direction collide with others walking in different directions [4]. The condition happens even though the platform is not crowded, causing delays. With proper coordination, in-vehicle interchange can deal with the cross-flow conflicts as storage medium (the platform) is not required. However, careful design on circulation of passenger flow inside vehicles is necessary, including the arrangement inside the train compartment and other transport management strategies such as educated passengers.



Fig 1.5 Passengers walking in different direction causing congestion
(Retrieved from: <https://www.flickr.com/photos/54690684@N07/6209131170>)

To facilitate in-vehicle interchange effectively, special vehicle coordination algorithm should be implemented. In this project, “branch and trunk” structure will be used to demonstrate the cross-region operation of the GRT system:

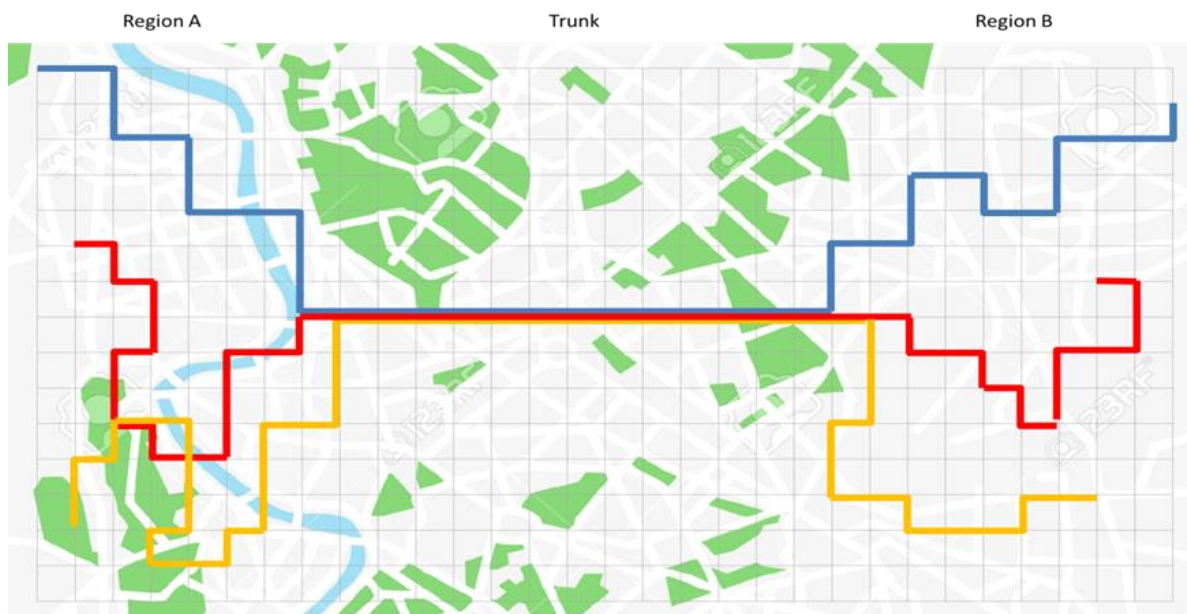


Fig 1.6 An illustration of city-wide network with “branch and trunk” operating procedure

Suppose a grid network of the GRT system is developed in a city-wide basis. In operation, the grid network is divided into regions. Passengers having the same O-D pairs (origin-destination pairs) are likely to be grouped into the same vehicles. First, vehicles are deployed to load passengers in the same origin region (region A) after screening their destinations. Passengers going to the same destination region (region B) are grouped into and collected by several vehicles. After collections, those vehicles move onto the same long straight section (the trunk). Vehicles couple together;

passengers interchange between vehicles according to the instructions provided by the operator. When reaching the destination region (region B), vehicles separate and discharge passengers in shortest paths.

The “branch-and-trunk” arrangement is expected to reduce the frequency of interchange by passenger matching. Only passenger trips going to the same region are grouped into the specific vehicles. This allows smooth ridership as passengers are likely to interchange only once. With the in-vehicle interchange system, the routes of vehicles can be more flexible, enhancing efficiency. The usage of vehicles is utilized by full-loading passengers with similar origin-destination pairs.

1.3 The Project Objectives

In this project, a scaled down model of a GRT system will firstly be built to illustrate the possibility of the implementation of such a system and to study its behaviors. The model will involve a lot of mechanical hardware (the rails, junctions, vehicles), electrical hardware (the motors, sensors, power electronics), and the control software in the microprocessor controller.

Then, simulations and calculations will be conducted to study the theoretical behavior of the GRT system. The simulations will be constructed using transport analysis computer software. Some mathematical equations and theories learnt in university lectures will be used to aid the calculations.

Finally, in reference to the results obtained from the above methods, concepts on GRT system design and implementation will be discussed. Summarizing the behavior observed, suggestions will be pondered and proposed if the GRT system is going to be implemented in the real world.

Overviewing This Report

In part 2, we will have a literature review on the inefficiency of existing transit systems, and indicating the merits of GRT outweigh the other systems will case study.

In part 3, the hardware model will be introduced in which mechanical and operational behaviors of a GRT system will be discussed. Meanwhile, in part 4, computer simulations and calculations will support the findings with theoretical values and expressions.

In part 5, an implementation guide of a GRT system will be drafted. Options on system design and specifications will be extensively discussed.

2.Literature Review

In an advanced city, transport is an essential element as it satisfies mobility needs of human activities. A good transport acts as the enabler of economic and social activities, supporting growth and development of the whole society. The Federal Transit Administration, U.S. Department of Transportation suggested the five groupings to categorize transit systems [5]. For an intelligent transit, it should consist of fleet management including automatic vehicle location, intelligent transit vehicles, automatic passenger counters, etc. Blythe et al. identified that intelligent transportation system can offer travel-demand management, infrastructure management, vehicle management, and information provision [5].

However, transits currently being used do not facilitate intelligent management strategies, causing traffic dislocations and deficiencies. For road transits such as buses, as they do not have their own infrastructures (buses have to share the road space with private vehicles), services drag down with heavy congestion in mixed traffic every morning. Passengers of transits suffer from uncomfortableness, losing their valuable time and money on unnecessary delay.



Fig 2.1 Although bus is a good tool in utilizing road space, it is impossible to force private drivers not to drive. Therefore, a good transit system should have its own infrastructure. (Retrieved from: www.tobinbennett.com)

2.1 Problems in Existing Transit Systems

Most mass transit services collect passengers in groups according to routed schedules. This has caused inherent inefficiencies. For passengers, time is wasted by waiting for the next vehicle to arrive, and often confusing or inconsistent schedules. For operators, scheduled service in off-peak hours may not utilize the capacity of vehicles. Some service, although the ridership is just 10% of the vehicle's capacity, still need to be provided under public authority policies (the policy headway). The inflexibility causes wastage on energy and resources.

Besides the scheduling problem, each of the different modes of transit has their own unsatisfactory:

2.1.1 Buses

In many large cities, existing road networks have reached limits of their capacities. Being a road transit, the efficiency of bus operations is dragged down heavily by the saturated road environment.

Road Fluid Dynamics

In a heavy but free-flowing traffic, jams can arise spontaneously, triggered by minor events such as an sudden braking, merging lanes at bottleneck, or simply by an extra car entering from an on-ramp [6]. Traffic waves, the traveling disturbances in the distribution of cars, are created and travel backwards relative to the cars.

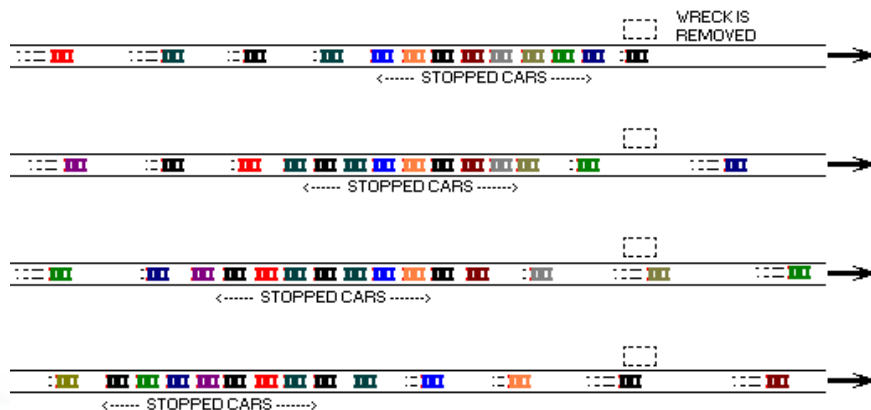


*Fig 2.2 A wave of "condensed" traffic creeps backwards
(Retrieved from: <http://trafficwaves.org/>)*

When a leading car brakes, the cars behind have to brake too. In contrast, when the leading car leaves, the following cars do not accelerate at the same instant. Each driver remains stopped for a 2-second reaction time. Each departing car must delay in the same way, and this causes the jam propagates to the upstream of the traffic.

The appearance of traffic waves is common in a congested traffic condition. Besides drivers' misses, traffic flow is often affected by signals or other events at junctions that periodically affect the smooth flow of traffic. The ease of creation causes difficulty in avoiding traffic waves, unless manual operation is totally replaced by automation.

Road transits such as buses are of manual operation, and the performance is discarded by randomness in behavior of drivers. Indeed, as buses have relatively low acceleration rate, other vehicles behind need to slow down or even stuck, causing delay. It is claimed that buses themselves contribute to road congestion in heavily-demand carriageways [7]. This can be frequently seen in some major distributors in Hong Kong, such as Nathan Road, that several buses queue to approach the bus stop.



Fig 2.3 Buses queue to approach stops causing congestion in distributor road

Under the combined effects of mixed traffic, buses delay frequently, causing inconsistent schedules. It is estimated that 32% of franchised bus trips in Hong Kong were unable to follow their travel schedules as displayed on the bus stops, and nearly all bus routes encountered problems of lost trips due to unexpected road conditions [8].

Many bus operators, such as Public Transport Victoria [9], have adopted bus tracking systems in order to reduce irritated passengers and their waiting time. Yet, the effectiveness of such a tracking system is questioned because of deviated arrival time prediction caused by unexpected road conditions. Researchers from University of Auckland pointed out that vehicles traveling at a slower pace increase energy inefficiency and contribute to pollution, justifying the implementation of intelligent transportation system [10].

Due to increased traffic popularity, public transport use has declined while congestion costs billions in wasted time, energy, accidents and pollution. However, automation on road is not likely within few decades due to capitals, technology constraints and public acceptance.

2.1.2 Railways

Railway is a typical example of automated transit, which has the advantage that every motion of a vehicle is under control. The use of guided rails enhances safety by preventing mistakes made by manual controls.

However, with conventional rail, in which the trains stop at every station, the closer the station spacing, the slower is the average speed. So to get more people to ride the system, the stations are placed far enough apart to achieve an average speed judged to be acceptable, but then ridership suffers because access is sacrificed. According to the research done by the Office of Rail Regulation [11], the accessibility of a transit hub is one of the major concerns of passengers. The long access time of railway stations favors the operations of feeder bus routes. Passengers may even commute by buses rather than railways as bus stops are usually located near-by.

Besides, the low passenger load factor (the percentage of occupied seats or space) of railway in off-peak hours causes intensive wastage on traction energy. Average load factor, in transit systems, is the ratio of the total number of riders to the total theoretical capacity. Policy headway is the maximum permissible headway as established by the transit agency or the policy board, usually for off-peak, low-demand periods. Despite the insufficient demand to meet the costs of supply, trains need to be departed in an interval not longer than the regulated policy headway, ensuring the provision of minimum service level [12]. Due to the infrastructural characteristic of railway system, it is impossible to reorganize train lines in a frequent manner. Demand-responsive service cannot be implemented in conventional railway systems. This inflexibility passively leads to energy wastage.



Fig 2.4 Train capacity is under-utilized in off-peak hours

2.2 Latest Transit Systems Similar to GRT

Some transit systems, which are similar to the GRT, are being proposed in different places in the world. Some of them are successfully implemented, and being the references of new transit projects in many advanced cities. Unfortunately, each of those systems has its own constraints and may not be suitable to have the same implementation in all places in the world.

2.2.1 The Bus Rapid Transit (BRT)

Bus rapid transit (BRT) is a bus-based mass transit system [13]. The BRT buses operate in a fully dedicated right-of-way, aligning in the center of the road, to avoid traffic congestion. Both buses and stations are specially designed to improve system efficiency and remove delay of typical causes. For instance, station platforms are built of level with the bus floor, and multiple doors for loading are provided for smoother boarding. Off-board fare collection is used to eliminate queuing passengers caused by on-board fare paying. Besides, BRT buses have higher priority at junctions in order to avoid signal delay.

BRT is more reliable and faster than regular bus services. It aims to combine the capacity and speed of light rail, low cost, flexibility and simplicity of a bus system. As the first BRT system built in Curitiba, many similar systems were inspired around Brazil and the world. As of October 2014, 186 cities in six continents have implemented BRT systems, accounting for 4,757 km of BRT lanes [14].



Fig 2.5 Labels showing the major components in a BRT system

However, the BRT has the following critical limitations which make BRT not the most suitable transit system to be implemented:

- **Necessity of Wide Road Space**

As the center lanes of road are partitioned for dedicated use, congestion will be induced to other road vehicles if the decided road section does not have wide-enough space. Including stations and other road auxiliaries, up to 20 meters of road space is preferred [15]. However, for some densely-developed cities, the roads are too narrow that insufficient road space can be reserved for constructing the BRT. For district distributors in Hong Kong, design standard of 20 meters 6 lanes two-way carriageway is used [16]. Due to intensive use of roads and high land price, expansion of road space is rather difficult in these developed cities. This makes the implementation of BRT infeasible.



Fig 2.6 BRT system in China uses up large portion of road space

- **Manual Operation**

The BRT system has a physically-separated right-of-way; conflicts with mixed traffic are unlikely. Still, buses are operated by human drivers, having a higher chance of accidents than automated control. Human mistakes such as collision when merging lane, hitting others at junctions, speeding, signal violation are possible under manual operation. Without the use of guided rail, accidents may occur due to skidding. The higher rate of accident than railway makes BRT not suitable to be implemented as elevated system, as elevation leads to difficult emergency rescue.



Fig 2.7 Two BRT buses crashed in Rio, Brazil (Retrieved from: <http://riotimesonline.com/brazil-news/rio-real-estate/brt-accidents-leave-more-than-130-injured-in-rio/>)

- **The Use of Fossil Fuels**

The use of diesel or gasoline-fueled engine in BRT buses raises environmental concerns. This violates the principle of sustainable development, as electricity generated by renewable energy should only be encouraged. If the BRT is built as underground system, without proper exhaust fan system, air pollutants will be trapped inside the tunnels and stations. Sulfur compounds in diesel exhaust causes potential health threats to drivers and passengers. In recent years, though the industry is moving to the use of hybrid electric bus instead of internal combustion engine [17], it is not cleaner than plain-electric propulsion.

2.2.2 The Personal Rapid Transit (PRT)

Personal rapid transit (PRT) is a public transport mode featuring small automated vehicles operating on a network of guideways. Its working mechanism is nearly the same as GRT, except the PRT vehicles are designed for travelling of individual and small group, typically carrying 3 to 6 passengers. The smaller structures translate into lower construction costs, smaller easements, and less visually obtrusive infrastructure [18].

Another difference with GRT is that nonstop, point-to-point service is provided by neglecting all intermediate stations. Wasting of time by indirect routes to their destination, stopping for passengers with other destinations can be avoided. Passengers can ideally board a PRT vehicle immediately upon arriving at a station. Privacy and the flexibility to choose passenger's own schedule are offered.



Fig 2.8 ULTra, at Heathrow Airport, London, is one of the few PRT systems implemented in the real world

However, the implementation of PRT was not as successful as BRT. As of 2014, only five PRT systems are operational. Opponents to PRT schemes have been raised by government regulators and institutes. Difficulty in large-coverage deployment was one of the major concerns [19]. As each PRT vehicle only carries 3-6 passengers, it would be far too small to meet the peak demand in large cities. In reality, 200 people would probably needs 75-100 cars since many would be selecting different destinations, many would choose not to ride with strangers, etc. Its low passenger-to-space ratio may cause pressure on network space and control systems. Queuing would be seen at junctions and stations, passengers feel uncomfortable with long waiting time. In other words, congestion within PRT system downgrades its efficiency and reliability. Although capacity can be expanded by large-scale infrastructure, some past projects have failed because of financing and cost overruns [20].



*Fig 2.9 PRT vehicles queuing at station (Retrieved from:
http://www.tdi.uk.com/uploads/527CFEE9E1607_500.jpg)*

2.3 Case Study – The Morgantown Rapid Transit

The **Morgantown Personal Rapid Transit (WVU PRT)** system (more correctly described as a Group Rapid Transit according to latest definition) is a people mover system in Morgantown, West Virginia, United States. The system connects the three Morgantown campuses of West Virginia University and the downtown area.

The Morgantown system is the world's "demand mode" fixed guideway transit system. Out of the small number of GRT systems implemented in the real world, the Morgantown system is a well-known example in transportation studies, and provides a valuable design template for future systems. The New Electric Railway Journal rated the Morgantown system as the best overall performer in its category [21].



Fig 2.10 The Morgantown Personal Rapid Transit

2.3.1 System Overview

The Morgantown system entered operation in 1975. The network consists of 8.7 miles of guideway serving five passenger stations and two maintenance facilities. When a car approaches a station it can either continue straight past, bypassing the station, or the wheels can turn and follow the electrified rails into the station. The vehicles are comprised of a fleet 71 rubber-tired electric vehicles each capable of carrying 21 passengers, 8 seated and the rest standing [22]. The track consists of concrete pathways with magnetic induction loops for providing system data.



Fig 2.11 The wheel of a WVU PRT vehicle

The system has three modes of operation: demand mode, schedule mode, and circulation mode [22]:

In demand mode, once a passenger enters a station and requests service to a destination, a timer starts. If the timer reaches 5 minutes, a vehicle is activated to service the request even if no other passengers have requested the same destination. Also, if the number of passengers waiting to travel to the same destination exceeds 15, a vehicle is activated. Once activated, a vehicle opens its doors and an electronic display prompts passengers to board. The vehicle doors remain open for 20 seconds allowing passengers to board. The doors close automatically, and the vehicle departs to its final destination, avoiding any intermediate stations.

In schedule mode, vehicles travel directly from origin to destination based on predetermined schedules. For high demand periods, schedule mode operates slightly more efficiently than demand mode.

During periods of low demand the Transit switches to circulation mode which operates like a local bus, stopping at each station along the route on a preset schedule.



Fig 2.12 Passengers waiting to board in peak hours

2.3.2 Observations from the Case

From the case study, there are key observations which help understanding the behavior of a GRT system:

- During peak demand periods, operating in either demand or schedule mode, the system transports approximately 1,500 passengers per hour, and carries roughly 15,000 passengers per day [22]. *The real data shows that the concept of GRT system is solid and feasible in supporting travel demand for daily human activities, say school trips to a university.*
- The system currently operates at between 98% and 99% availability [22]. It has completed 110 million passenger-miles without serious injury. The only reported accident happened in 2016 when two cars were involved in a crash [23]. *Because of full-automated control, the safety of a GRT system is much better than the conventional, non-automated modes of transit.*
- The Morgantown system switches from demand-response to fixed schedule service in order to solve high demand in peak hours. *Such algorithm shows high degree of flexibility and provides a template for peak-demand solution in new GRT system design.* The average wait for passengers traveling between the two busiest stations during peak demand is about 1 minute [22]. *The GRT can be said as capable in handling peak demand, with strategic planning on operating procedures.*
- The vehicle demand at each station is estimated based on current passenger requests and past travel patterns. When a station shortfall is detected, empty vehicles are routed to the deficit station from surplus stations [22]. *The efficiency of a GRT system is greatly affected by the logic of the control system. It should have the ability of collecting trip data continuously, analyzing passenger behaviors and travel patterns, and applying the results in aiding vehicle routing. More importantly, sufficient vehicle depots should be distributed, providing stand-by locations for quicker demand response.*

2.4 The GRT – Why It Is Superior

Many researches reviewed the advantages of the GRT over the other transit systems. The Office of Technology Assessment, Congress of the United States reviewed the key advantages of GRT over the other transit modes [24]:

- I. Nearly point-to-point service with few stops on its own right-of-way
- II. High availability at all times of day due to automation

Guala, transport planner involved in Masdar City, experimented that when the strategy of GRT is put into a personal rapid transit (PRT) system, the capacity can be tripled [25]. Research team from University of Southampton commented “GRT offers the advantages of a tram with the flexibility of a bus” [1].

The advantages of GRT can be further elaborated by the following points:

Grade-separated Right-of-way

Grade separation is the separation of different flows of traffic at different heights (grades) so that they will not disrupt each other. In railway construction, elevated system and underground system are two grade separation methods isolating the railway from road traffic. Such systems are granted as right-of-way (ROW) category A – fully controlled ROW without crossings or any legal access by other vehicles or persons [26].

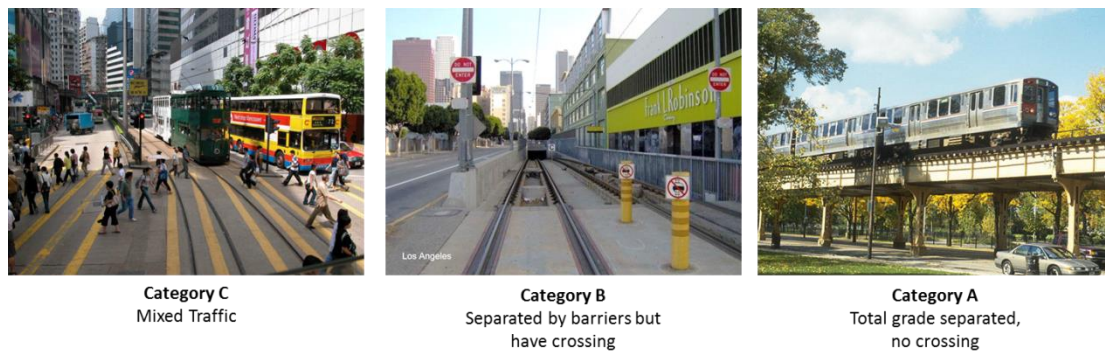


Fig 2.13 Right-of-way categories – a comparison

Several researches have been revolving the use of exclusive right-of-way for GRT system. Research from University of Auckland highlighted the expansion of development is a three-dimensional maze, and tends to vertical growth [27]. Chapman suggested that congestion can be alleviated by transferring public transport into an exclusive system, such as an elevated system [5]. Extension of capacity is also possible by building layers of networks with unlimited underground space. This is crucial to many large cities, as expansion of road space in these cities is rather difficult due to developed road networks and high land price. Avoiding topographical constraints, development in underground tunnels can be expected.

The use of exclusive ways prevents unexpected interruption by other types of transports. Together with automation, it greatly reduces the chance of accidents, ensuring smooth journeys. Passengers using public transports do not need to bear the consequences, say congestions, brought along by private car users.

Automated System

Automation reduces unnecessary delay caused by manual operation. A powerful logic system can handle multiple tasks in microseconds, that human cannot. In the operation of GRT, automation helps routing by calculating the shortest path according to passenger calls. Automation optimizes junction coordination - vehicles can pass the junction with least deceleration and free from conflicts. Automated vehicles can travel close together. Possibilities include dynamically combined "trains" of vehicles to reduce drag and increase speed, energy efficiency and passenger density.

Also, it improves ridership experience, as accurate time prediction can be guaranteed to passengers. Together with guided rails, the GRT system is free from human mistakes and weather influences such as skidding. The high degree of safety is already proven by relatively low accident rate of railway systems.

Densely-populated Network

Unlike conventional railways, stations of GRT are densely distributed. Vehicles travel along a network of guideways, much like a network of streets. There are stations located near passengers' homes and working places. Passengers can have easy access, time cost is reduced. With a citywide deployment with many lines and closely spaced stations, passengers are able to travel citywide without shifting to other transport modes. The GRT can take relatively direct routes to their destinations without leaving the vehicle. Research from Royal Institute of Technology, Sweden pointed out the possibility of applying GRT as efficient feeding/distribution systems around heavy rail stations [28].

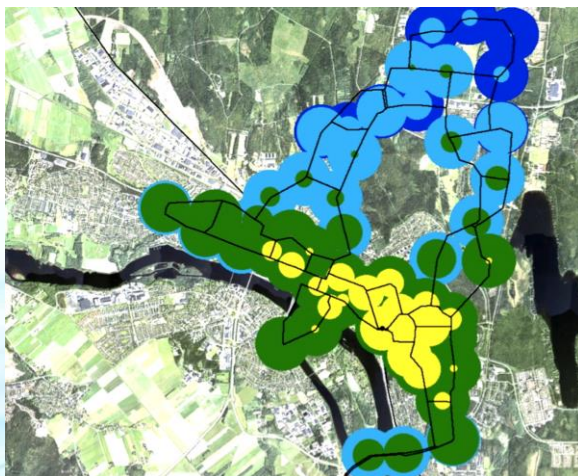


Fig 2.14 Simulation has been conducted to prove the time suitability of using GRT as feeder transport connecting heavy rail station. The combined usage of GRT and heavy rail can be effective in handling peak loads [28].

With a relatively smooth ridership substantially faster than cars in areas with heavy traffic, some private car drivers may be attracted to use the transit rather than driving. Simulation suggests that GRT would actually attract not only trips from private cars, bicycle and walk but also from bus services [29]. It is estimated that total ridership can increase by up to 135% if local bus service is replaced by GRT [29].

High Flexibility

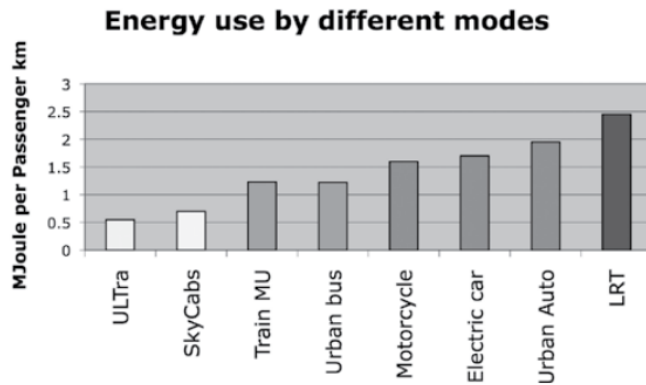
The operation of the GRT can be described as a horizontal elevator – passengers call the vehicles when they need the service. When other passengers “press the button” to request for services, the vehicles stop at these middle stations to pick those passengers up. The control system does the routing of vehicles after matching the travel demand, which means the route of a vehicle is always different time by time. This demand-responsive capability can utilize the capacity of a vehicle meanwhile maintaining acceptable efficiency to passengers [1].

The key ability of GRT outweighing the conventional railway is that the GRT is capable to shift from demand-responsive service to fixed-route service when needed [24]. In peak hour, the passenger volume is so large that there would be very high chance to gather 30 passengers going to the same destination in a single origin. The temporary shifting to fixed-route can release the burden of routing calculations by the central system in peak hours. In contrast, it is difficult to for conventional railway to shift from fixed route to demand-responsive service.

Energy Utilization

The demand-responsive algorithm of GRT can be a useful technique in utilizing traction energy in off-peak hours. Scheduled mass transit, such as buses or railways, trades off between service frequency and load factor. Those transits must run on a predefined schedule, even during off-peak hours when demand is low and vehicles are nearly empty. This makes the transit vehicles consumes a lot of unnecessary energy. On the other end, the GRT can match passenger demand with vehicle capacity, and then design the most efficient route in picking the passengers. This can save the traction energy by not going to unnecessary stations [24].

Together with driverless control, the GRT can provide 24-hour service – passengers can take the GRT at any time they want [24]. With comprehensive use of energy-saving detectors and sensors in peripherals (station lighting, air-conditioning, escalators, etc.), the GRT can serve passengers in all time without many of the costs of scheduled mass transit.



Source: European Community Final Report (2004)

Fig 2.15 Energy use by different modes, in which SkyCabs is a proposed GRT system by University of Auckland [5]

Technical Feasibility

All the system components and operating approaches stated in the previous parts are proposed base on existing technologies. Indeed, the implementation of GRT needs cooperation from different aspects, such as comprehensive transportation strategic planning, technical research and simulation, machinery and programming, local traffic condition and environmental surveys.

2.5 Summary to Literature

GRT is considered as not just a transit, but the ultimate public transportation solution for a future smart city. The world is developing in a trend that pursuing higher mobility, faster migration of population and more intensive human activities. The intent of implementing GRT is to transplant public transportation completely from surface roads to an isolated transit network. Passengers using transits do not need to bear the consequences, say congestions, brought along by private car users. The masses can enjoy a comfortable, efficient and safe journey with reasonable cost. Satisfying highly demanded mobility, GRT will take the place of road transports being the final transportation mode in the future.

However, evidence supporting the feasibility of GRT in reality is still inadequate. Wade denoted that forerunners GRT systems have been in operation for several years, but no major deployments have been seriously considered [30]. The Urban Mass Transportation Administration was criticized for not performing important computer simulations and other studies to indicate the configurations of a GRT [24]. The GRT contains uncertainty and therefore has the value to be studied comprehensively. The theory remains active and there is room for discussions on the possibility of implementing GRT.

3. The Hardware Model

In this project, a scaled down hardware model of a group rapid transit system (GRT) is built to illustrate the possibility of the implementation of such a system and to study its behaviors. The model involves a lot of mechanical hardware (the rails, junctions, vehicles), electrical hardware (the motors, sensors, power electronics), and the control software in the microprocessor controller.

From the hardware model, the following outcomes are expected:

- A network organized as “branch-and-trunk” structure (mentioned in part 1.2) should be constructed to demonstrate the cross-region operation of the GRT system.
- In the trunk section, the two model vehicles should be able to demonstrate the “in-vehicle” interchange operation by physically coupled together. After reaching the destination, the two vehicles separate.
- Passenger movements inside the vehicles should be visible in order to clearly observe how the passengers are arranged. Therefore, a graphical-user interface program should be written.
- The computer program should also allow the user to customize the origin-destination (O-D) pairs of the passengers. Then, the system should implement the vehicle routing and network arrangement according to the user’s choice.
- By observing the performance of the hardware model under different scenarios, the behavior of a GRT system can be preliminarily evaluated. The observations may aid drafting the system design and implementation guide of GRT system in part 5.

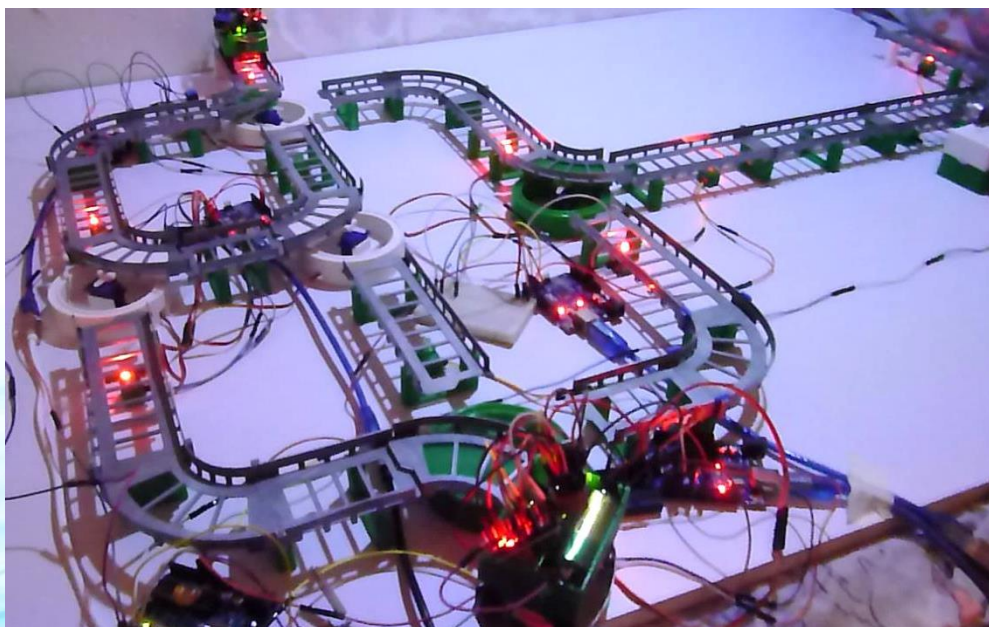


Fig 3.1 The hardware model – a panoramic view

3.1 The Major Components

The hardware model comprises of three major components: vehicles, network of tracks and central computer. Within each of the components, microcontroller is embedded as the processing unit enabling various functionalities.

Arduino is a computer hardware and software company that designs and manufactures microcontroller kits for building digital devices [31]. Arduino board uses a variety of microprocessors and controllers. The boards are equipped with sets of digital and analog input/output (I/O) pins that may interact with customized expansion circuits. The board features serial connection for communicating with personal computers. The Arduino software is published as open source tool, letting users writing and uploading their programs onto the Arduino boards.

In this hardware model, two types of Arduino board, Arduino Uno and Arduino Pro Mini, are selected. Arduino Uno is the most-used medium-sized board with relatively high reliability and stability. It features sockets for all input/output pins; users just need to connect the pins by inserting jumper wires without soldering. The easy-to-use characteristic makes the Uno being used in most parts of the model. Arduino Pro Mini is the smallest-sized board in the series. Its low cost and incredible small size (1.8mm x 3.3mm) make the Pro Mini suitable to be used in the model vehicles.



Fig 3.2. Arduino Uno



Fig 3.3 Arduino Pro Mini

3.1.1 The Vehicle

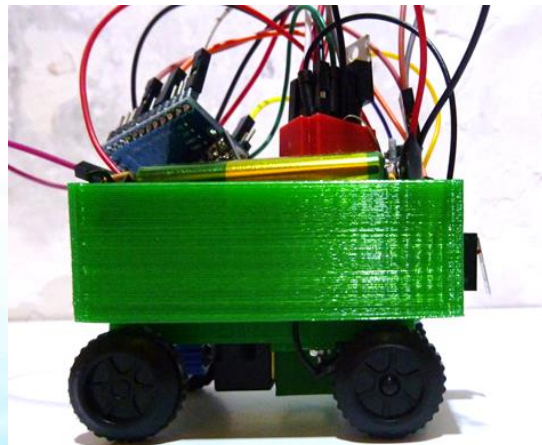
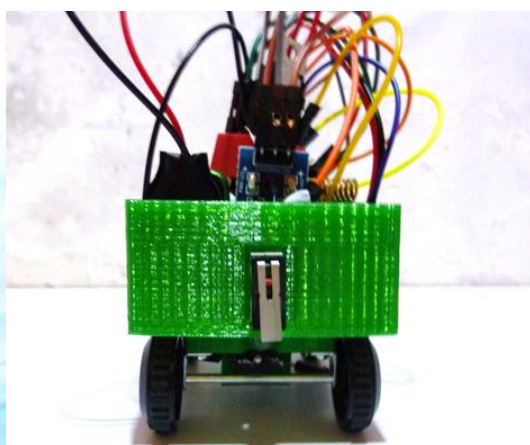


Fig 3.4 The model vehicle (front view, side view)

The model vehicle is a unit of propulsion demonstrating running operation of a GRT vehicle. In total two vehicles (vehicle A and B) were built. Each vehicle comprises of the following power electronics and electrical parts:

<u>Part</u>	<u>Description</u>
Geared motor	DC motor having a gear ratio of 1:1000, 30 rpm no-load under 9V power supply. Blocked torque of 10kg.cm ensures the model vehicle running without overloading.
Arduino Pro Mini	The microcontroller controlling all the functionalities. Receiving signals from the light sensor and the mechanical switch, the Pro Mini controls the rotation of the geared motor and communicates with the central computer through RF transmitter.
Light Sensor	The sensor is facing to the ground. When an LED is detected at stations and junctions, the light sensor sends signal to the Arduino board for further action (Fig 3.6). As the sensor is encased by a transparent LED bulb, it senses light beam from single direction without fooling by environmental lighting. The sensitivity is adjustable.
RF transmitter	433MHz ASK module radio-frequency transmitter. It facilitates wireless radio-frequency signal transmission from the Arduino Pro Mini to the central computer.
Power transistor	TIP41C NPN BJT in TO-220 plastic package. The collector is connected to the motor, the emitter is connected to ground, and the base is connected to the Arduino. Arduino can control the transistor via pulse-width modulation (PWM), which in turn controls the motor's speed.
Diode	When a motor stops, there is the potential for a small amount of current to be generated as the shaft continues spinning. The 1N4001 diode placed in parallel with the motor leads to keep any generated electricity from damaging the circuit.
Mechanical switch	Installed in the front of each vehicle. When the two vehicles couple, the mechanical switch will be pressed. Arduino senses the pressing and transmits corresponding signal to the central computer.
Gears and wheels	Rotation of the geared motor is transferred to the wheels through series of gears.
Mini breadboard	Constriction base for the circuit without soldering
Chassis	Self-designed 3D-printed PLA chassis loading all the components. It is assembled by M2 screws.

9V battery

Two 9V batteries are used – one for the Arduino Pro Mini and one for the motor

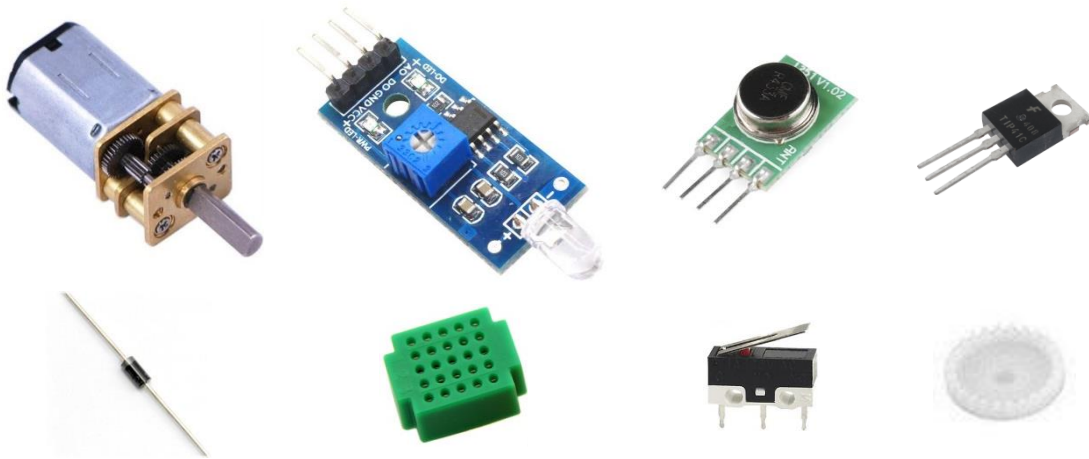


Fig 3.5 (From upper left) geared motor, light sensor, RF transmitter, Power transistor, diode, mini breadboard, mechanical switch, crown gear

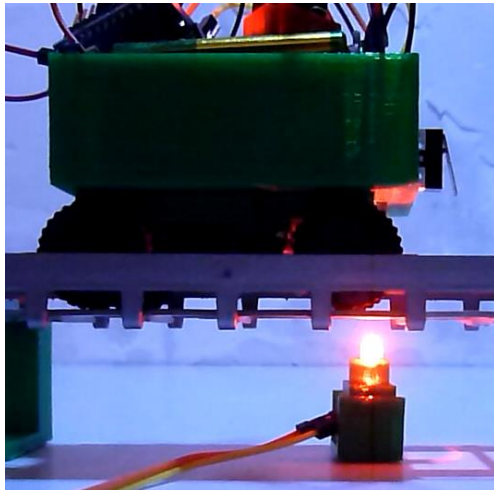


Fig 3.6 The vehicle stops when sensing an LED

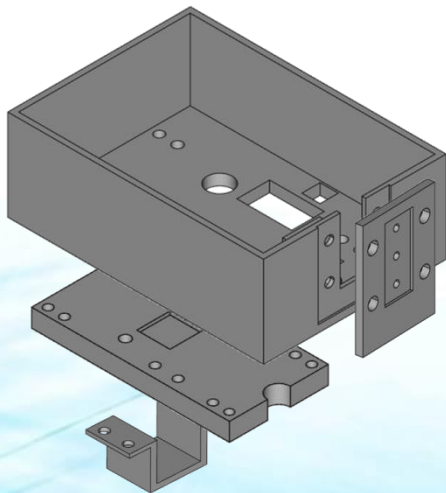


Fig 3.7 Chassis produced by 3D printing

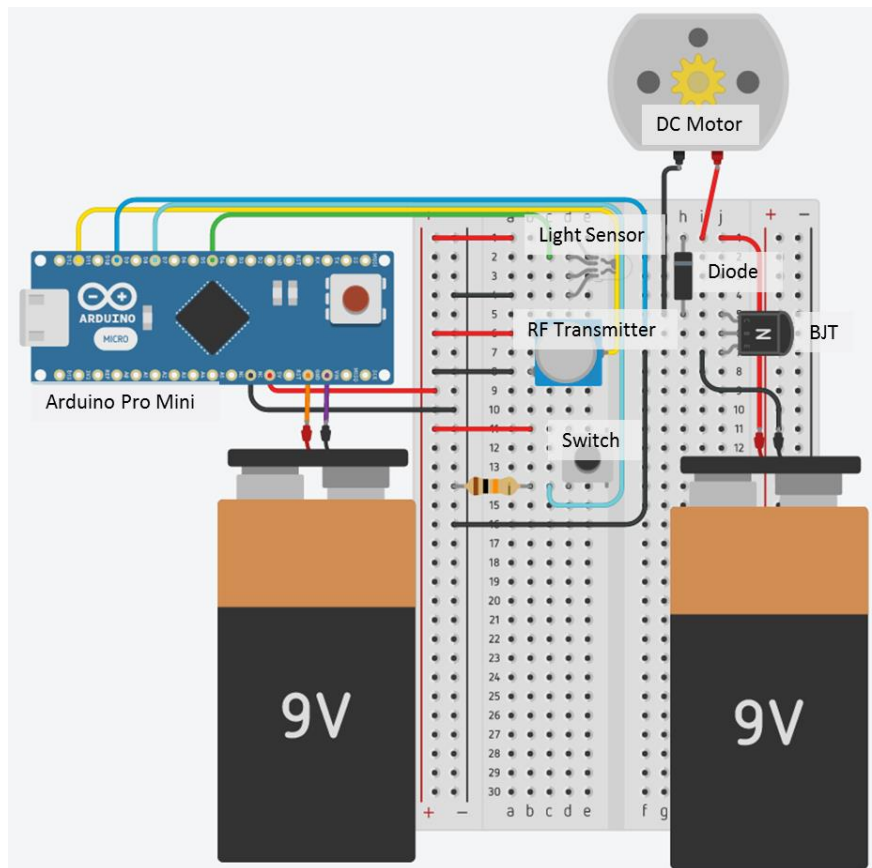


Fig 3.8 Circuit diagram of the model vehicle

3.1.2 The Network

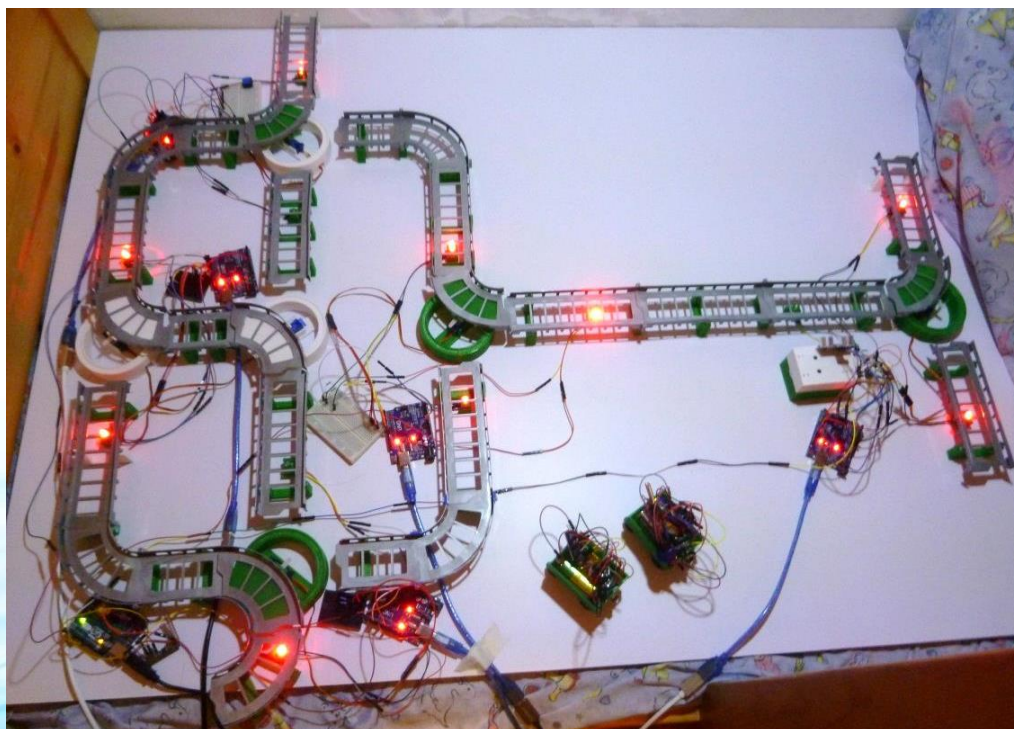


Fig 3.9 The model network (top view)

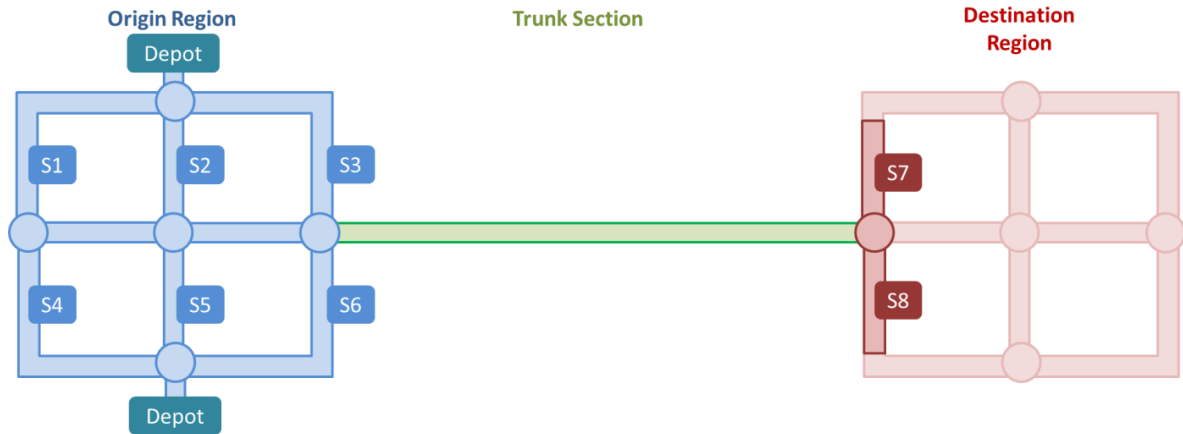


Fig 3.10 The schematic of the model network

For the model network, the “branch and trunk” structure is constructed to demonstrate the cross-region operation of the GRT system. On the left hand side, a 4-square grid network is representing the origin region. Six stations are set in this region. Two vehicle depots are set at two ends of the grid. In the middle of the network, a trunk section is set for the coupling of the two vehicles. At the end of the trunk, the two tracks separate and extend to two stations of the destination region.

For the regional network, one-way system is implemented. The movement on any branch within the grid is limited to one direction. It is simple to implement without excessive policing. Although “go straight” movement is disabled, the one-way system approach enhances safety due to reduced conflicts (Fig 3.12). Signal coordination can also be improved in junction by the reduced turning movements. It is estimated that the implementation of one-way system can reduce accident rate by 10 - 50%, and the improved signal coordination can reduce junction passing time by 10 - 50% [32].

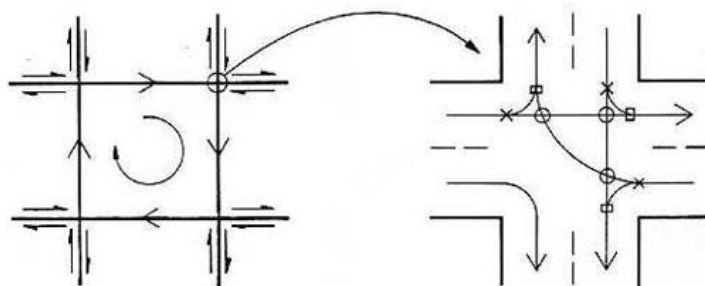


Fig 3.11 The one-way system with turning movements indicated

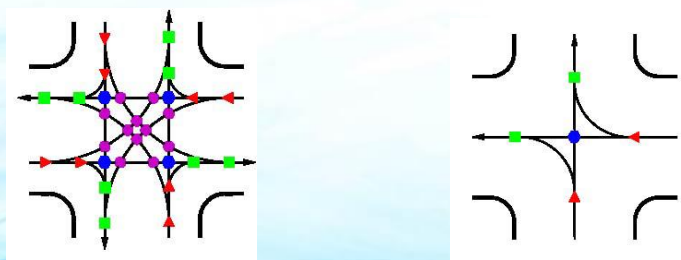


Fig 3.12 Compared with two-way operation, the one-way operation has less turning conflicts

Tracks

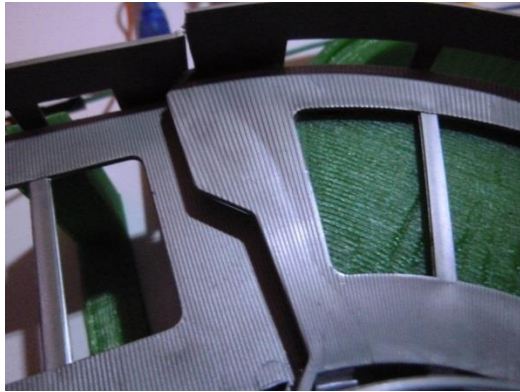


Fig 3.13 The grooves on the track surface

The guideway-type plastic tracks used in this model were taken from a remote toy car kit. The grooved pattern on the track surface provides better friction. Together with the rubbered tires, the vehicles can run smoothly without skidding. Two types of base are specially designed and manufactured using 3D printing. The bases elevate the tracks to match with the height of the junctions.

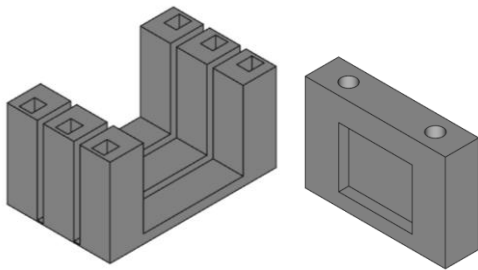


Fig 3.14 Two types of base are produced using 3d printing

Stations & Other Stopping Points

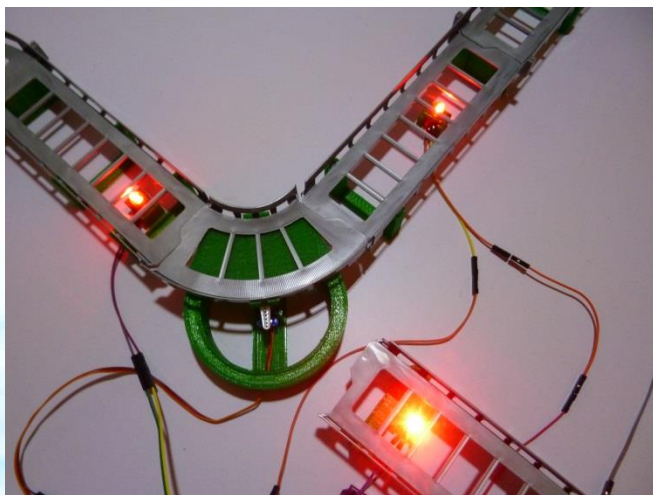


Fig 3.15 Station LEDs under the tracks

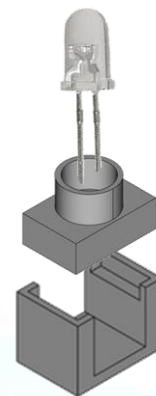


Fig 3.16 An LED base

A 5mm red LED light is installed at each location of the stations (including depots and trunk) under the tracks. The LED glows, indicates the specific station that the vehicle should stop by. The LED will be turned off after the vehicle has picked up the passengers at that station, and the junction ahead is ready for passing. An LED base is specially designed and 3D-printed for holding the LED bulb.

In addition, an ultrasonic sensor is placed near the end of the trunk section. When the ultrasonic sensor senses the passing of the leading vehicle, the LED under the trunk will be triggered, stopping the following vehicle. Because of this set-up, the separation of vehicle can be achieved.

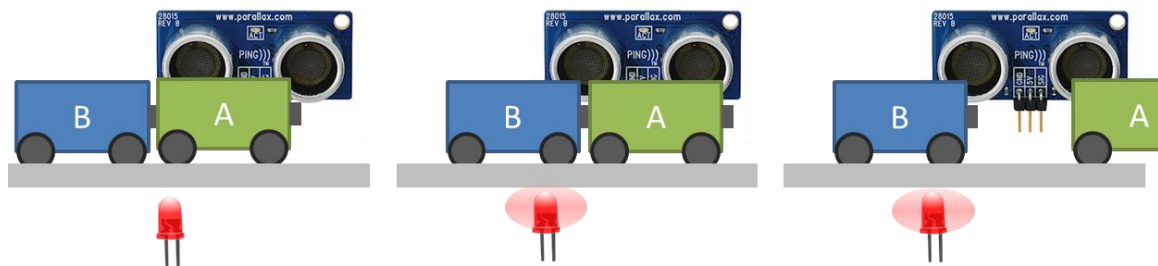


Fig 3.17 When the ultrasonic sensor senses vehicle A, the LED is triggered to stop vehicle B

Junctions

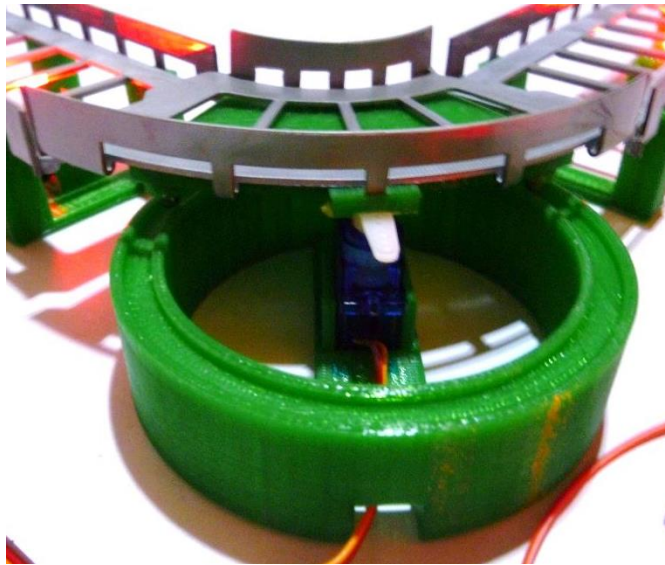


Fig 3.18 A junction

The turntable-type junction comprises of a curved track, a SG90 micro servomotor, an Arduino Uno board and a self-designed 3D-printed junction base. The junction Arduino is connected to the central computer through jumper wires. The central computer sends signals to the junction Arduino according to different stages of operation. The junction Arduino then processes the signal and commands the servomotor to turn for a specific angle. For simpler circuit, the station LED and ultrasonic sensor are also connected to some specific junction Arduinos.

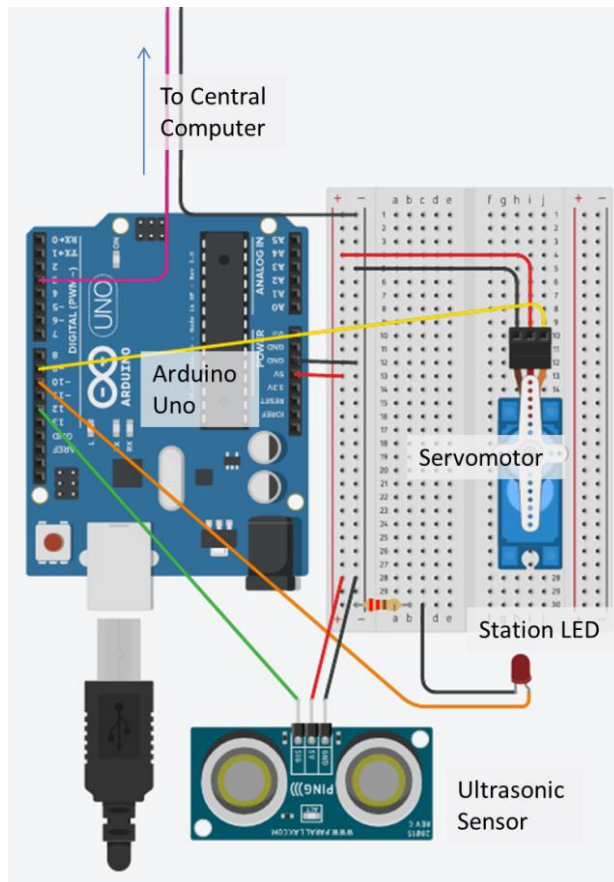


Fig 3.19 Circuit diagram of junction

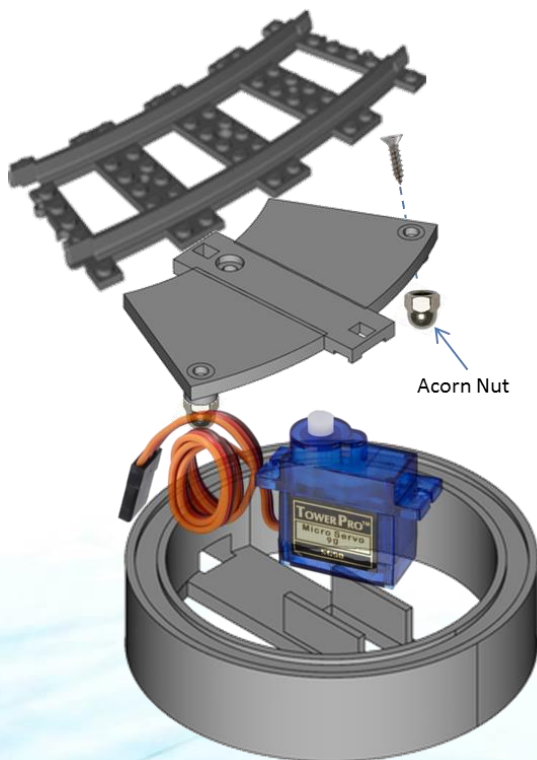


Fig 3.20 Structure of junction

3.1.3 Central Computer

The central computer comprises of a 433MHz ASK module radio-frequency receiver on an Arduino Uno board, connected to a notebook computer with the monitor program opened. The monitor program is used to observe the passenger arrangement inside the two vehicles. It is a Windows form program written by C# language. The program communicates with the Arduino Uno board by serial connection.

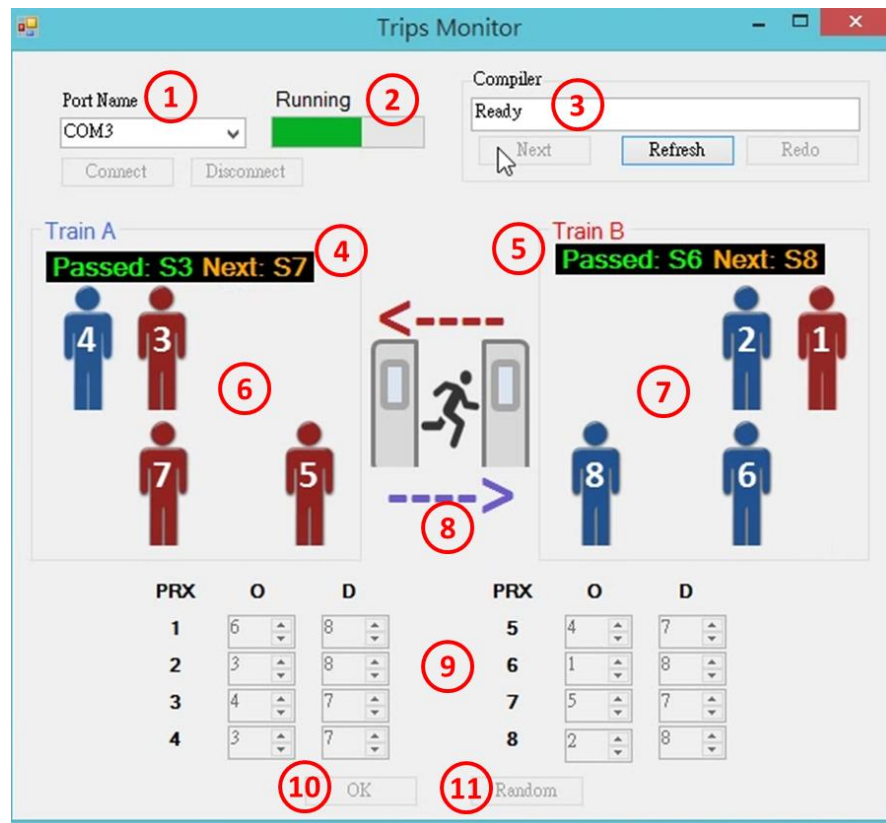


Fig 3.21 The monitor program (description of elements in the following table)

Element	Description
1	Serial connection set-up
2	Progress bar showing current progress
3	Compiler, which initializes and sends user data to the Arduino Uno, is activated after the “OK” button is pressed. The textbox shows serial feedback from the Arduino Uno, with editing functions attached. The user can check whether error occurs while compiling.
4	Passed station and next station of Vehicle A
5	Passed station and next station of Vehicle B
6	Compartment of vehicle A. Passengers originally boarding vehicle A are indicated by blue man icon.
7	Compartment of vehicle B. Passengers originally boarding vehicle B are indicated by red man icon.
8	This image is displayed when the two vehicles couple together in the trunk section. Passengers who need to interchange will move to the opposite vehicle.

9	Selection of O-D pairs for 8 passengers. The range of origin station is station 1 to station 6 (origin region in Fig 3.10), and the range of destination station is station 7 and station 8 (destination region in Fig 3.10).
10	The “OK” button is pressed after the user confirms the O-D choices. The simulation starts after the compiling.
11	Generating random values to passengers’ O-D pairs.

In the program, the user is firstly allowed to customize the passenger O-D pairs. When the choices are confirmed by pressing the “OK” button, the program notices the central Arduino board for initializing and starting the simulation. In different stages of operation, the central Arduino receives vehicle signals from RF communication. The embedded program in the Arduino then calculates the current condition of the system, and reflects the results on the program interface including locations of vehicles, boarding/alighting of passengers, vehicle coupling in trunk and the corresponding passenger interchange. The central Arduino also coordinates all the junctions in the system. After calculation, it sends signals through jumper wires, commanding junctions to turn for specific angles.

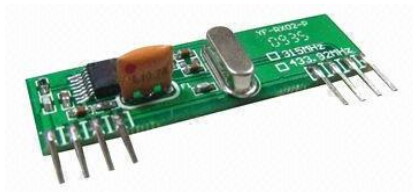


Fig 3.22 RF receiver

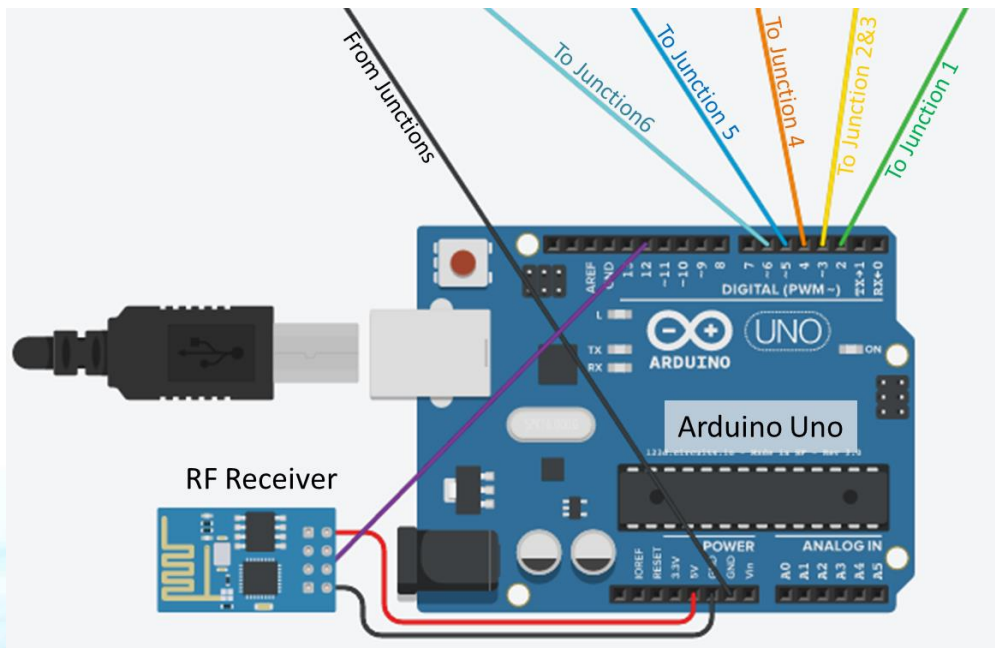


Fig 3.23 Circuit diagram of central Arduino board

3.3 Mechanism & Algorithm

The interaction of hardware between components can be represented by the following block diagram:

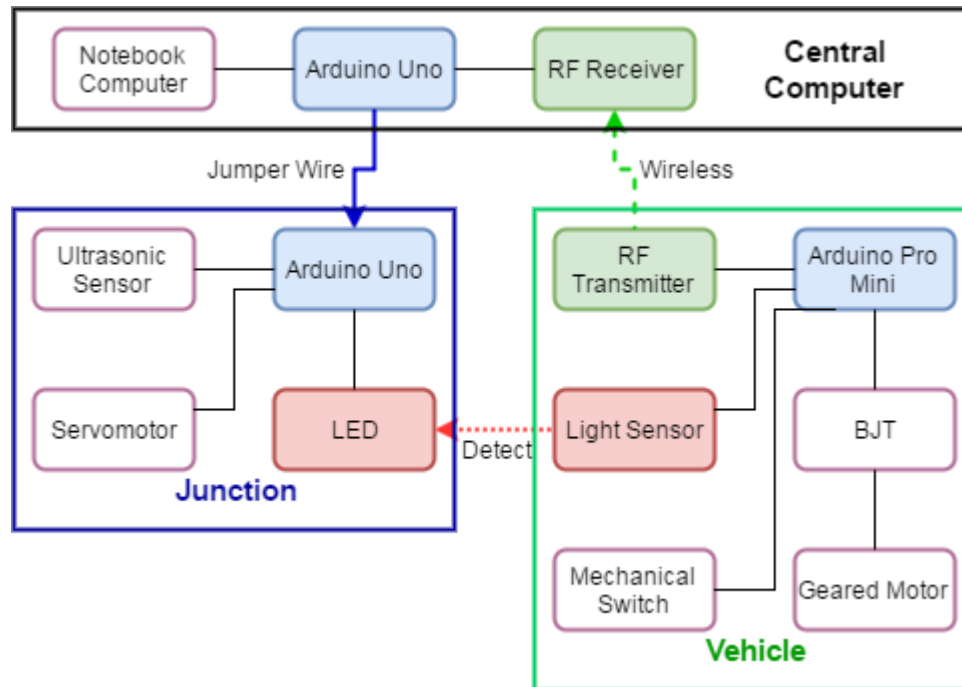


Fig 3.24 Block diagram of the model system

The communication channels play an important role in component interactions. The LEDs in junctions command start/stop of vehicles through light sensing. The vehicles detect the fluctuation and communicate with the central computer through radio-frequency signals. In response, the central computer tells the junctions to modify their LEDs through jumper wires. Thus, a complete communication loop is formed between the three components.

In the software aspect, the program in each component intensively interacts with each other, and the whole operation can be divided into iterations. Although the algorithms used are all in sequential access, infinite loops can be set for repeated actions. Vehicle motor is programmed to run except the light detection or mechanical switch interferes. Patterns are preset inside each junction, and the received signal tells which pattern the junction should use.

After the central computer calculates the routing, signal is sent which tells the junctions to change to specific patterns. Such modification triggers the vehicles to start running. When the vehicle senses the next LED light and stops, signal is sent to central computer wirelessly. The central computer calculates and updates accordingly, and tells the junctions to change to the other patterns. This iteration continues until the vehicles finished their journeys.

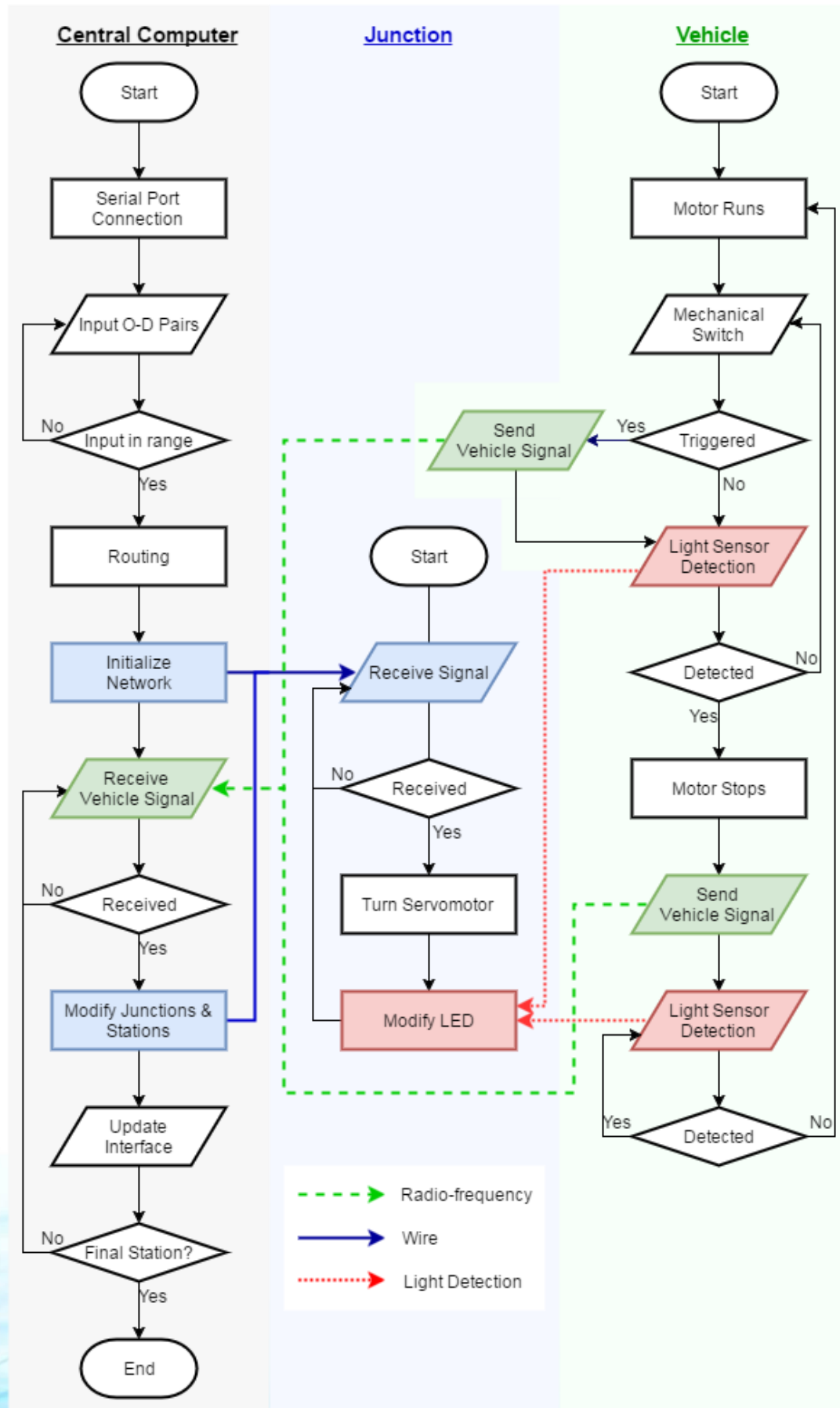


Fig 3.25 Flowchart of Algorithm

3.4 Model Operation – A Step-by-step Navigation

In the following, the flow of full operation of the hardware model will be shown in a step-by-step manner.

- 1) Open the monitoring program in the notebook computer. Connect to the serial port with the Arduino board attached.

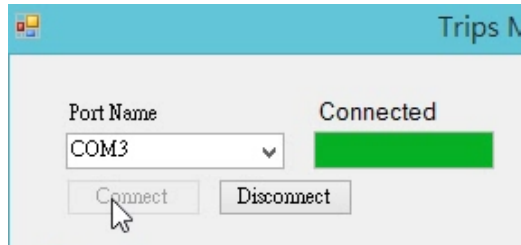


Fig 3.26 Connecting the serial port

- 2) Customize the O-D pairs of the passenger. The range of origin is Station 1 to Station 6, and the range of destination is Station 7 to Station 8. Random combination can be generated by clicking the “Random” button for simplicity.



Fig 3.27 Customizing O-D pairs

- 3) Click the “OK” button to finish customize. Read the instructions in the compiler. Arduino boards can be refreshed by pressing the reset button on the board. After refreshing all the Arduino boards in the model, click “Next”.

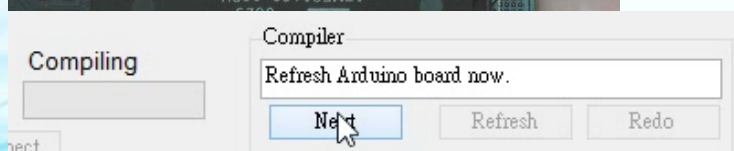
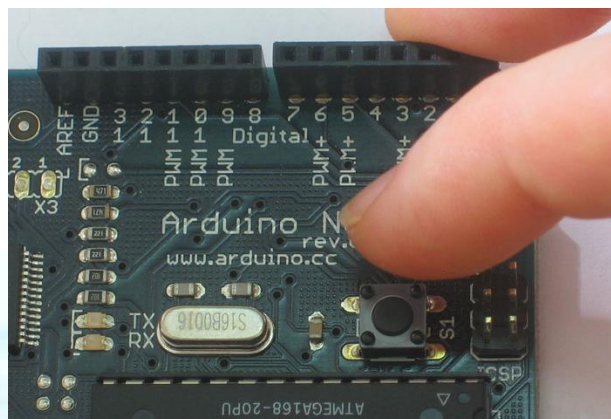


Fig 3.28 Resetting a Arduino board

- 4) The stations and junctions will be initialized automatically. When the rotations of junctions are completed, click “Next”.

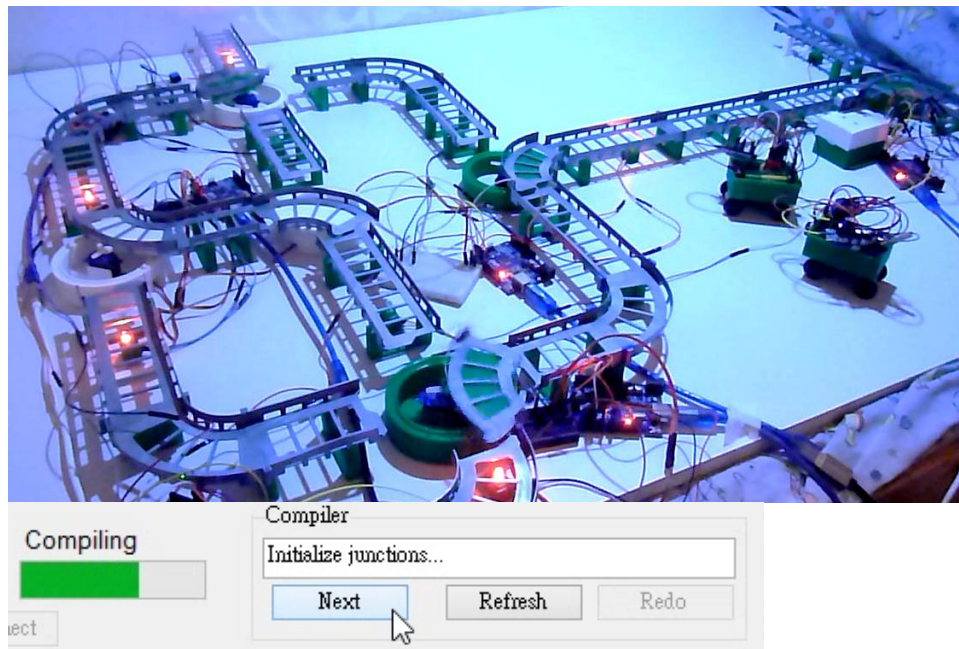


Fig 3.29 Junctions will turn to specified positions automatically

- 5) Turn on the vehicles and put them onto the depots. The vehicles will move and stop at the positions of LED. Then click “Next”.

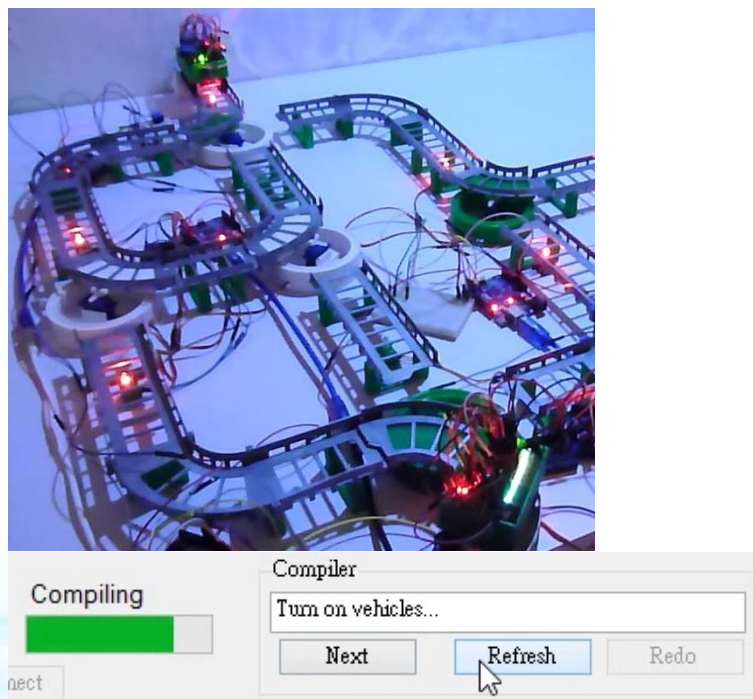


Fig 3.30 Putting the vehicles onto the track

- 6) Now the initialization is completed. Click “Next” to start the simulation.

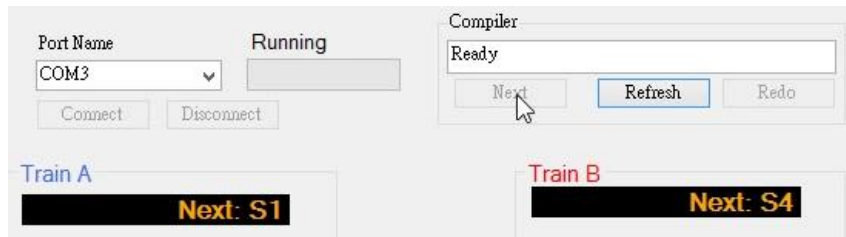


Fig 3.31 Starting the simulation

- 7) The depot LED will be turned off and the vehicles will start to run. When a vehicle arrives to a station, passengers will board the corresponding vehicle. Passengers boarding vehicle A will indicated as “blue man”, and passengers boarding vehicle B will be indicated as “red man”.



Fig 3.32 Passengers boarding the vehicles

- 8) The vehicle will stop for 5 seconds if the station has boarding passengers. After 5 seconds, the station LED will be turned off, and the vehicle will run. The junctions will turn automatically in different progress of operation.

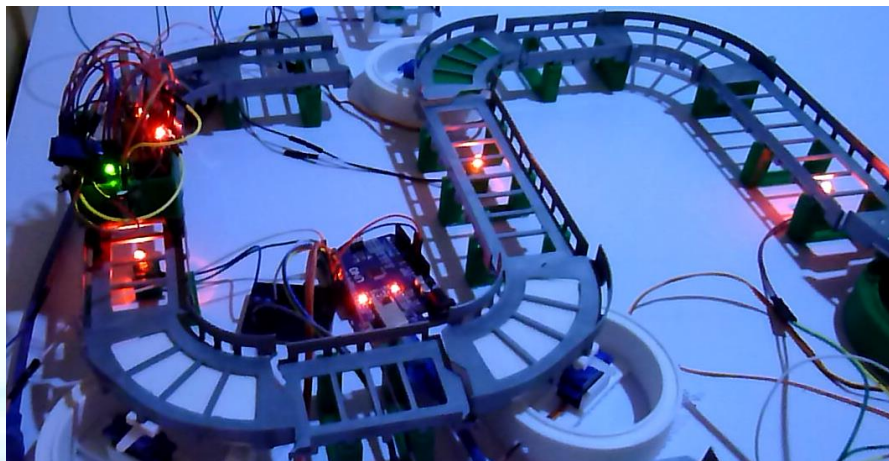


Fig 3.33 Vehicle A stopping at Station 1

- 9) When entering the trunk section, the leading vehicle will stop at the LED position.

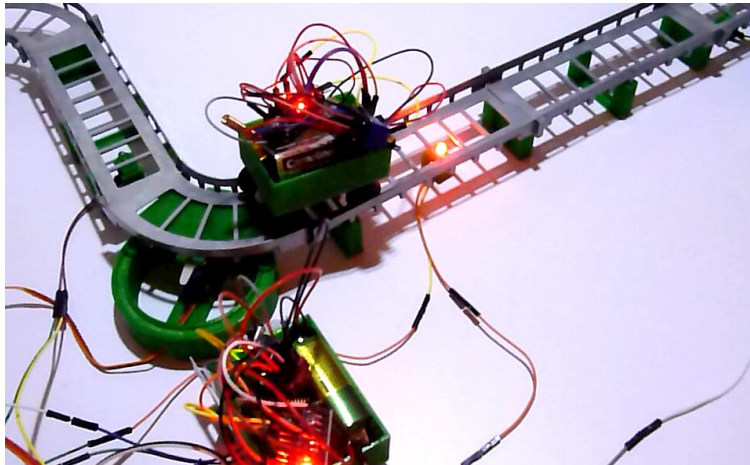


Fig 3.34 Vehicle A enters the trunk section



Fig 3.35 Arrangement of passengers before interchange

- 10) Then, the following vehicle enters the trunk section. The mechanical switch at the front will be pressed when the following vehicle contacts with the leading vehicle. The interchange of passengers will be shown on the program interface.

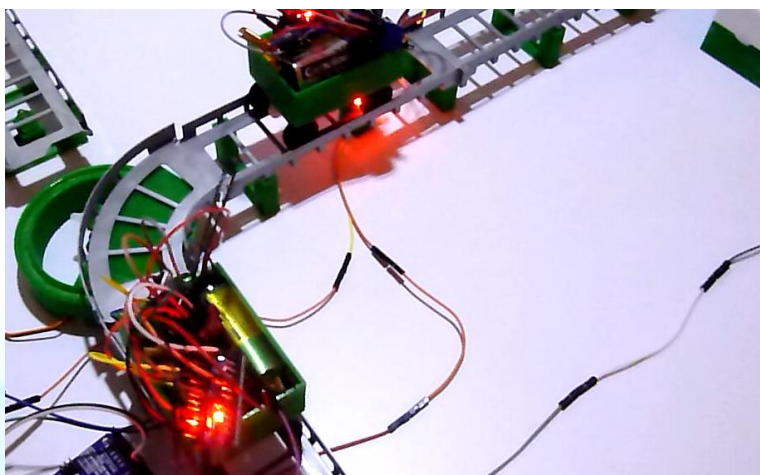


Fig 3.36 Vehicle B enters the trunk section

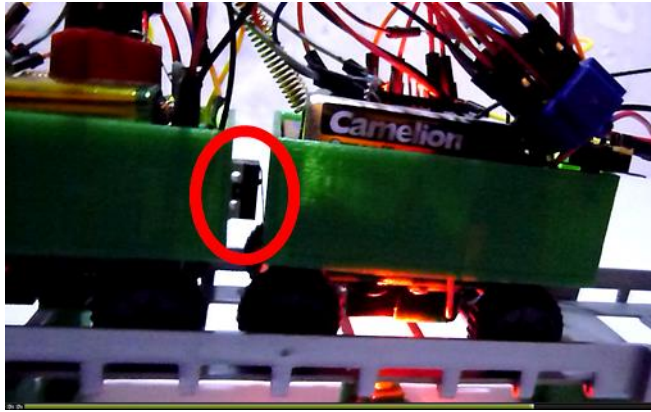


Fig 3.37 The mechanical switch of vehicle B is pressed

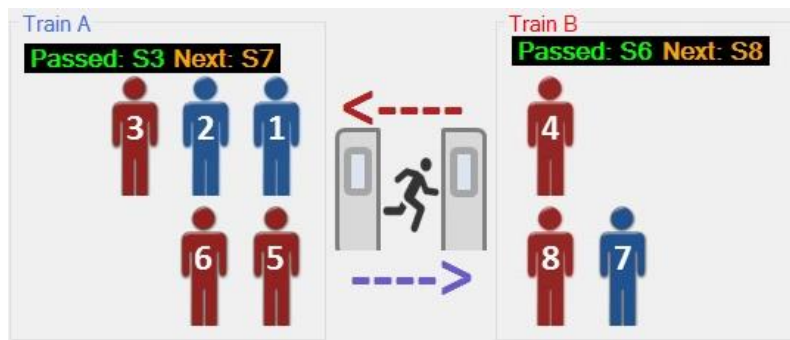


Fig 3.38 Arrangement of passengers after interchange

- 11) The two vehicles will run through the trunk section while coupling. When the leading vehicle is detected by the ultrasonic sensor, the LED under will be turned on, stopping the following vehicle.

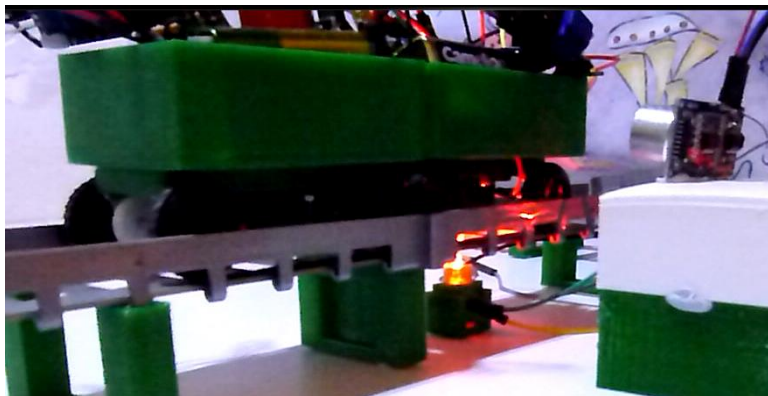


Fig 3.39 The ultrasonic sensor detects the vehicle and triggers the LED

12) The two vehicles separate. The program shows that the interchange is over.

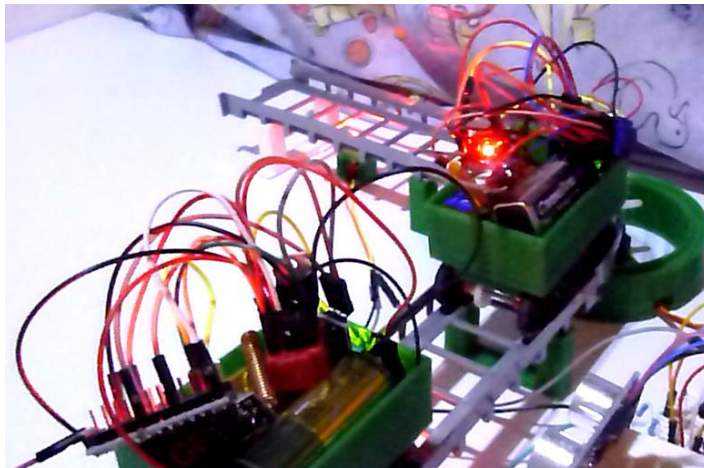


Fig 3.40 Separation of vehicles



Fig 3.41 The interchange image is omitted

13) The two vehicles arrive to the destination region. The simulation finishes.

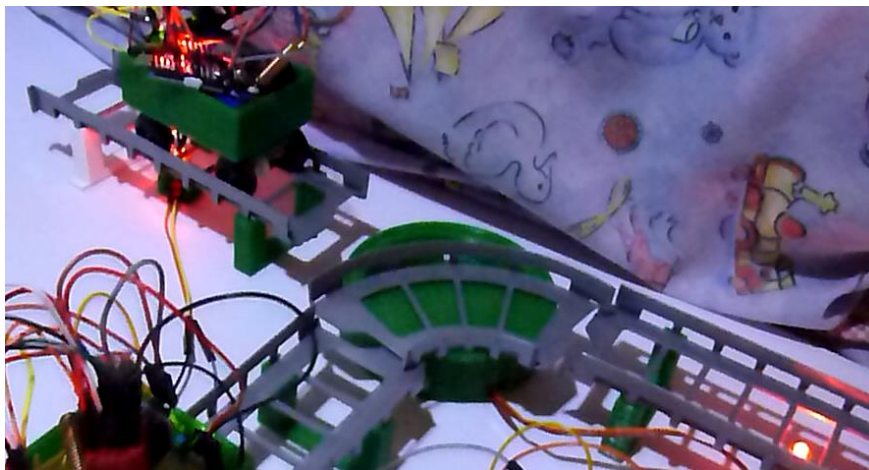


Fig 3.42 Vehicle A has arrived Station 7

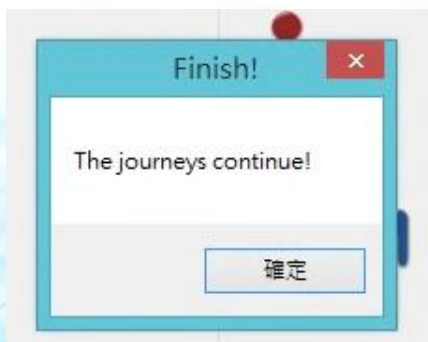


Fig 3.43 Imagine the two vehicles continue their journey

Note:

The system will assign different routes according to the customized passenger O-D pairs. For instance, when no passenger boards the vehicle at Station 1 and Station 2, the vehicle goes to Station 3 directly from the depot.

PRX	O	D	PRX	O	D
1	5	8	5	6	8
2	4	7	6	3	8
3	4	8	7	6	7
4	5	8	8	6	7

OK Random

Fig 3.44 No passenger boards the vehicle at Station 1 and Station 2

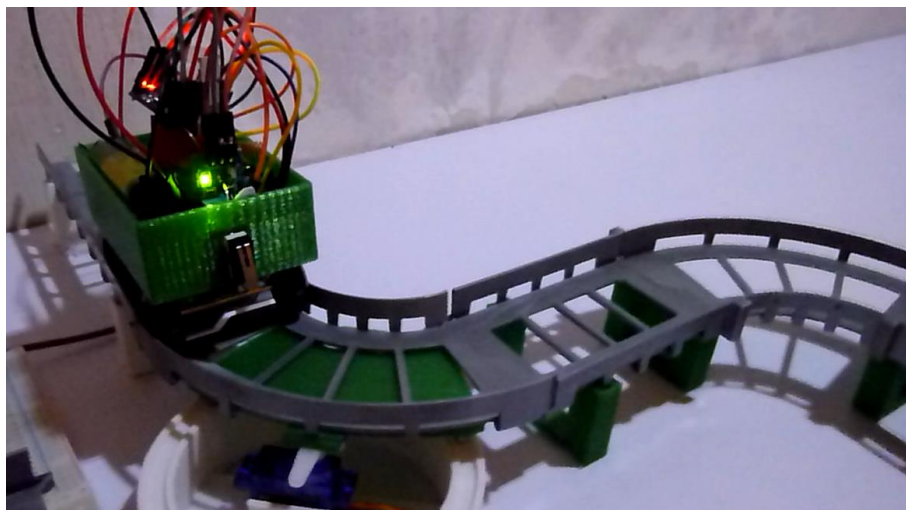


Fig 3.45 Vehicle A turns left and goes to Station 3 directly

3.5 Results of Hardware Model

Results of Operation

- The hardware model was successful in demonstrating the “branch-and-trunk” region-to-region operation approach, under different combinations of passenger O-D pairs.
- In the trunk section, the two model vehicles were able to demonstrate the “in-vehicle” interchange operation, with passenger movements inside the vehicles visible in the computer program.
- The computer program allowed the user to customize the origin-destination (O-D) pairs of the passengers, and the system was able to implement different vehicle routings and network arrangement according to the user’s choice.
- Summarily, the hardware model has given us a brief image about the operation of GRT in a smooth and specific way.

Measurement Results

- Speed of travel (in region) = 1.18 cm/s
- Speed of travel (on trunk) = 1.3 cm/s
- Travel time between stations (in region) = 43 sec
- Total time operating the whole network = 5 min 25 sec
- Duration (from entering the trunk to coupling) = 27 sec
- Travel time on trunk (coupled) = 26 sec
- Duration (from separation to leaving the trunk) = 47 sec
- Buffering time after coupling = 1.5 sec
- Total stopping time of vehicle A = 67 sec
- Total stopping time of vehicle B = 137 sec

Matrix of Trip Time (sec)

From\To	1	2	3	4	5	6	7	8
1		46	137				241	269
2			91				195	223
3							104	132
4					97	145	254	272
5						48	157	175
6							109	127

Analysis

1. The trip times from stations in region A to stations in region B were similar despite which vehicle the passenger took. This showed that the “branch-and-trunk” operation is effective in averaging the trip times among passengers.
2. The total duration of coupling was 74 sec, which takes about 30% of the largest trip time. Besides, total stopping time of vehicle B is much longer than that of vehicle A due to the separation. These values showed that the coupling method used in the model is not efficient enough (more discussion in part 4.2).
3. Delay of vehicle B at station 5 was up to 54 seconds because vehicle A was still in the next section of the track. The same happened in vehicle A at station 2. However, in a real GRT system, vehicle B should instead link with vehicle A, forming a “train of vehicles” (more discussion in part 3.6).

The above analysis shows the delay caused by quality constraints of hardware components and insufficient intelligence of algorithm, while the delay shall possibly be absent in a real GRT system.

Obviously, the values of the hardware model do not have a significant meaning in studying the actual performance of a real GRT system. It is expected that the real GRT has more precise technical specifications and sophisticated algorithm intelligence. Indeed, we will have a computer simulation session in part 4 to find out the theoretical behaviors of a GRT system.

3.6 Discussion on Observed Behavior

From the GRT hardware model, the following behaviors were observed:

I. The importance of data processing power of control system

The possible combinations of passenger O-D pairs can be a huge number. In the hardware model, each passenger can have up to 12 possible O-D pairs. Then, a configuration of 8 stations with 2 vehicles means 360 possible routing combinations. In a real GRT system, due to the demand-responsive operation, the passenger trips can appear in any location at any time. With a much larger network than the model, the amount of routing combinations can be massive.

Therefore, the control system should have the ability to find the best solution out of the large number of combinations. *The algorithm should be effective in allocating thousands of passengers into several vehicle routes.* The routes should be time efficient while utilizing vehicle capacity as much as possible. This involves strong data processing power of the system server.

In peak hours, shifting from demand-responsive to fixed schedule service can be a good technique. As mentioned in part 2.4, the fixed schedule operation can release the burden acting onto the system server, by reducing the number of calculations. The task of server is then switched to telling which vehicle the passenger should take, instead of doing trip assignments. This makes us understand why the Morgantown system, discussed in part 2.3, implements the mode-shifting technique.

II. The junction design influences system performance

In the hardware model, railway turntable design is used in junctions. A railway turntable is a device for turning railway vehicles. A track is placed on a circular platform, and the platform rotates to connect different directions of tracks. The turntable in the hardware model can finish its rotation in 1 second. Yet, in reality, due to the larger size and weight, the rotation of turntable is much slower. Also, the turntable allows only one turning movement at the same time, but not multiple. Vehicles may need to wait for the turntable to rotate, causing delay and congestion. Thus, it is unsatisfactory to be used in a busy system, where frequent turning demand is required.

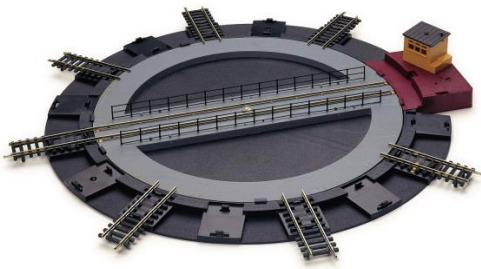


Fig 3.46 Railway turntable



Fig 3.47 Railway switch

Instead the turntable type, switch type should be suggested in real GRT system. A railroad switch is a mechanical installation enabling railway trains to be guided from one steel track to another. The switch consists of the pair of linked tapering rails lying between the diverging outer rails. It can be moved laterally into one of two positions to direct a train coming from the upstream toward the diverging paths. In operation, switching of rail is a moment's notice. Multiple turning movements are also possible at the same time.

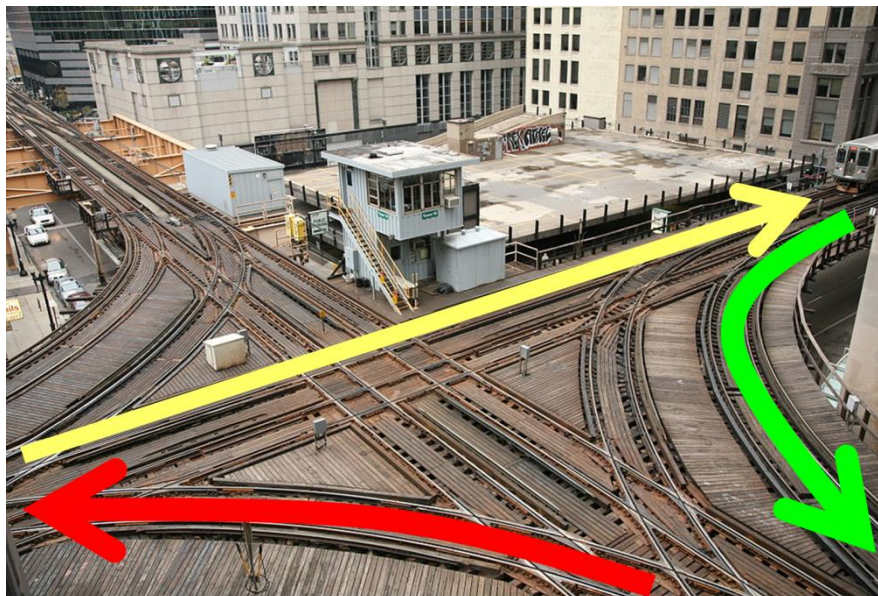


Fig 3.48 Multiple turning movements are possible in railroad switch crossover

Channel guideway system can be another considerable design. In the Morgantown Transit, vehicles steer by means of side guidewheels that sense the location of the left or right curb (Fig 3.50). Switching is accomplished by directing the vehicle to steer either left or right until the guidewheels sense the corresponding guiderail [22]. However, for steering in guideway, accurate alignment with the curb needs to be performed under slower speed than that on the steel rail; and rubber tire is less reliable than steel wheel.

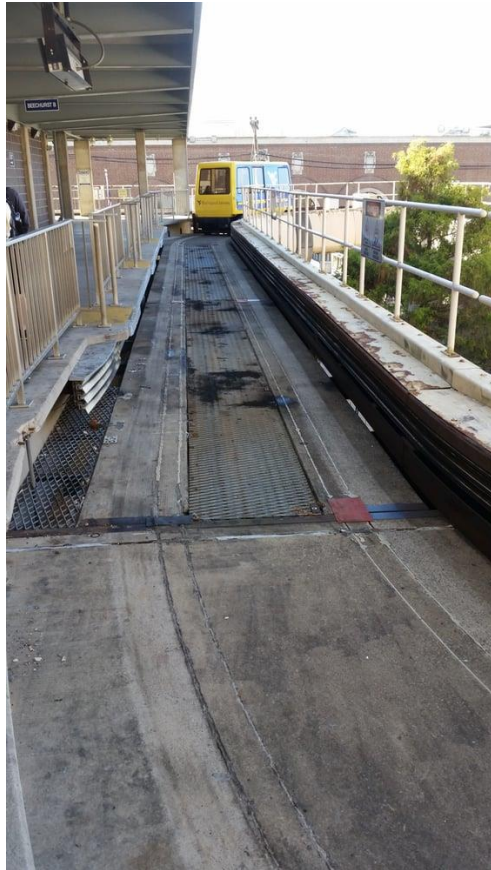


Fig 3.49 Guideway in the Morgantown Transit

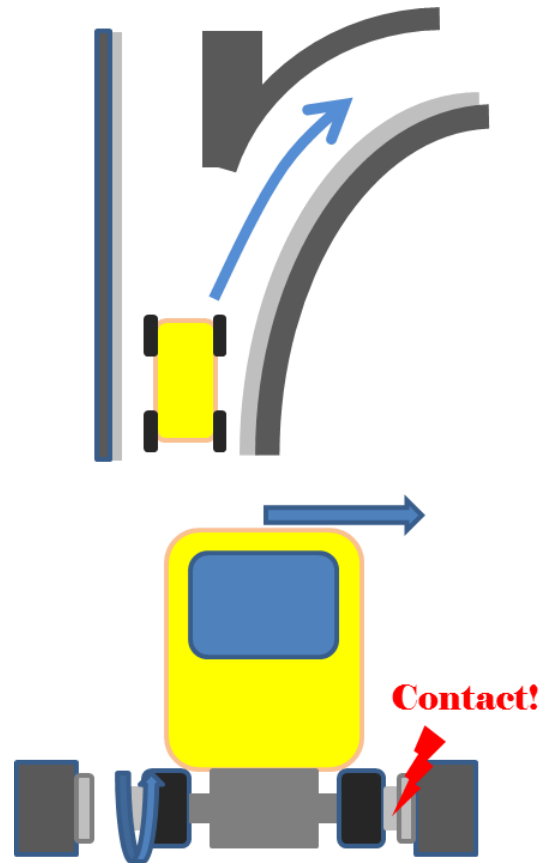


Fig 3.50 When steering, the wheel aligns with the side curb

III. Efficiency can be enhanced by vehicle linkage

Block signaling may not be an efficient choice for GRT system. In the hardware model, the regional network is divided into sections known as blocks. In normal circumstances, only one vehicle is permitted in each block at a time. Vehicles cannot collide with each other because they are not permitted to occupy the same section of track at the same time. This gives the system a high level of safety but sacrifices blocks of spaces.

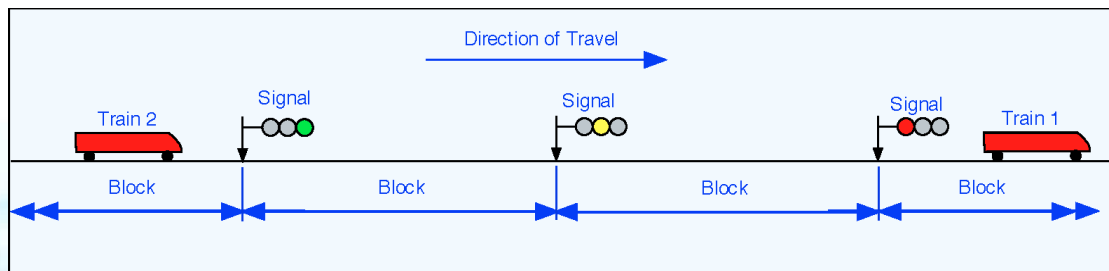


Fig 3.51 Block signaling

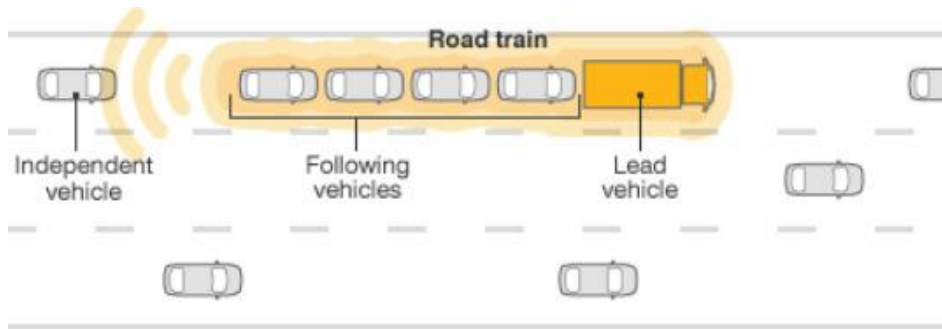


Fig 3.52 The concept of “train” of vehicles

The GRT should be an intelligent transit. As mentioned in part 2.4, the gap between successive vehicles should be zero, forming a “train” of vehicles. In regional network, “train” can be formed by keeping vehicles at constant speed without physical linkage (coupling); in trunk, vehicles must be coupled physically due to in-vehicle interchange safety and high-speed operation. The density of vehicles in the network can be more compact, eliminating block-signal waiting time. This needs intelligent vehicle coordination: *accurate distance-measuring equipment should be installed on each GRT vehicle*. Fast Coupling and separating of vehicles should be facilitated for improved efficiency. *The vehicle motor should be sensitive in response to speed change requests*, otherwise collision occurs.

IV. Route coordination determines branch-and-trunk’s success

The interchange operation of trunk involves coupling of several vehicles. In other words, those vehicles must arrive to the entrance point of the trunk at the same time. If one vehicle has delay, other vehicles have to stop and wait, blocking other unrelated vehicles. Thus, before sending vehicles, the control system should have *comprehensive and accurate prediction about the time need in each route*, and the time point when the vehicles gather. When vehicles are operating on their assigned routes, real-time tracking of locations is necessary in checking whether they run as predicted. *If tolerance is found, the system should be able to recover by balancing the vehicles’ progresses*.

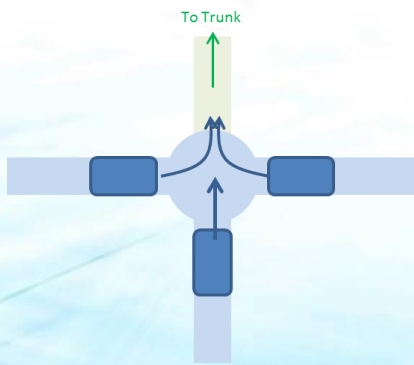


Fig 3.53 Vehicles must arrive to the trunk at the same time in order to interchange

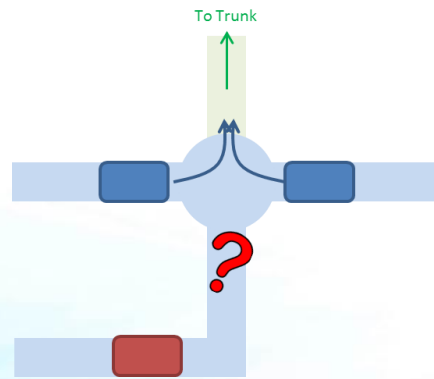


Fig 3.54 If one vehicle has delay, others have to wait

However, delay may be induced by random passenger behavior in a real system. For instance, a passenger blocks the train door and that train departs 10 seconds late. This may make the in-vehicle interchange fails. Therefore, the system ability in dealing with unexpected condition, such as balancing the progresses of other vehicles by slightly increasing their station dwell times, is important. Besides technical methods, the performance of system can be guaranteed by *well-educated passengers*.

V. One-way system can be good and bad

In one-way system, each track is restricted to allow only one direction of flow. Reverse in direction is not allowed even though that section of track is not occupied. In the hardware model, the one-way system, together with manual calculation, *effectively reduces the number of routing combinations* into 5 routes. Besides reduced routing algorithm complexity, location assessment of stations is expected to be much simpler in real transport planning.

However, *trip detour can be frequently observed in a one-way system*. Consider a vehicle travels from Station 1 to Station 2 (Fig 3.55 & 3.56). Under two-way operation, the vehicle can go to Station 2 by taking the straight route. Yet, under one-way operation, the vehicle suffers from extra travel distance and time. Though the overall system performance can be improved, some routes may have to lose. The one-way system is suggested in congested central area, as junction efficiency can be improved by reducing conflict movements (part 3.1.2).

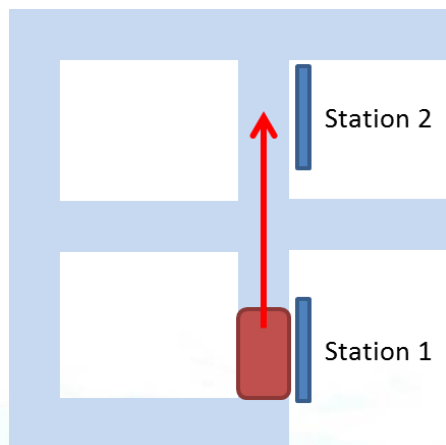


Fig 3.55 Under two-way operation, the vehicle can go to Station 2 directly

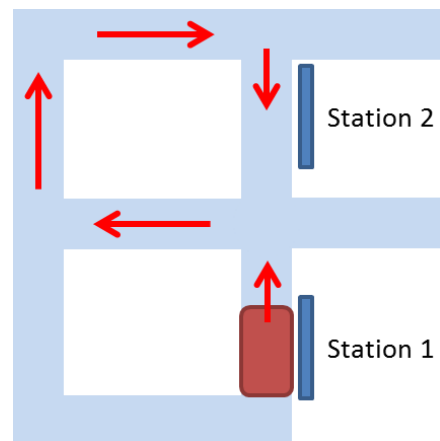


Fig 3.56 Under one-way operation, the vehicle travels detour

VI. Side track and off-line station

In the hardware model, stations are set on the single track. Imagine a vehicle is dropping passengers at a station, and another vehicle, which wants to pass that station, comes behind. Obviously, the vehicle behind cannot pass the station due to the

stopped vehicle. In a real GRT system, large number of vehicles is expected to pass the same section of track within minute, like road vehicles. System performance would have a dramatic decline; queue of vehicles can be seen in every station.

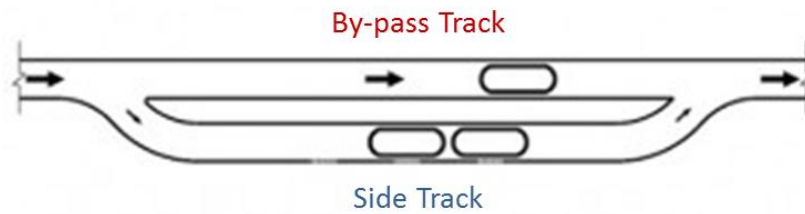


Fig 3.57 Off-line station

An off-line station comprises of a by-pass track, and a side track for picking up or dropping off passengers. Off-line station allows vehicle by-pass without deceleration. It effectively reduces number of stops, which minimizes trip time. Off-line station permits the vehicles to wait at stations when they are not in use instead of having to be in continuous motion. Thus, it is not necessary to stop operation at night – service can be available at any time of day or night. Besides, off-line station can be sized to demand, whereas in conventional rail all stations must be as long as the longest train. It is also suggested that side track can be built on trunk section in case of waiting vehicles.

VII. In-vehicle interchange should be implemented in off-peak only

In in-vehicle interchange, at most half of the passengers in a vehicle will be request to move. The movement between vehicles should be “one-in-one-out” – two passengers swap their standing spaces. If interchange happens among two full-loaded vehicles, passengers just cannot move – the opposite vehicle has not space for me to move in, but if I do not move, I cannot leave a space for an opposite passenger to come in.



Fig 3.58 There is no space for people moving in a full-loaded train

The algorithm of trip assignment should be of high intelligence in allocating passengers with least interchange movements and least detour. Basically, the interchange vehicle cannot be full – adequate space should be reserved for movement buffering. *Balance between vehicle capacity utilization, time efficiency and smooth interchange should be accomplished.*

Shifting from demand-responsive to fixed schedule service in peak hours is advisable. As passenger volume is high, it is rather easy to find out passengers with the same O-D pair. They can be packed into scheduled vehicles, no interchange is needed thus utilizes vehicle capacity.

VIII. Vehicles should physically coupled together when interchange

The model vehicles in the hardware model do not “link” together. The trick is to slight reduce the speed of the leading vehicle, so the following vehicle “pushes” the leading vehicle and they appears “linked” visually. Obviously, such trick cannot be implemented in the real vehicles due to safety concerns.

In real in-vehicle interchange, rather than just maintaining the coupling vehicles at a constant speed, *coupling should also be formed*. Mechanically, it is difficult to make two motors running at exactly the same speed - a slight speed tolerance is expected. Forming a coupling can compensate such speed tolerance, thus gap will not appear accidentally in the middle of the linkage.

More clearly, “coupling” in GRT means vehicle connection by physical mean (coupler), while “linking” means forming a “train of vehicles” without physical connection (Fig 3.52).



Fig 3.59 Coupler of two trains

Comment

From the hardware model, operational and mechanical behaviors of a GRT system were substantially observed. Yet, evaluations on numerical values (such as travel time) were inadequate due to the simplicity of the model. In part 4, computer simulations and mathematical calculations will be conducted to obtain the performance of a GRT system in a theoretical way.

4. Simulations and Calculations

In this part, the behavior of the GRT system, under various options of operations, are observed by conducting traffic simulations. The differences on trip time and system capacity are calculated according to the results of the simulations. Mathematical expressions can then be formed by relating variables obtained in parts. (In this part, values highlighted in yellow are important values.)

Specifications of Vehicle

Before designing simulation scenarios, the vehicle specifications in this project's GRT system are firstly assumed.

In the real world, automated people mover (APM) is a type of driverless grade-separated mass transit system generally used for serving relatively small areas such as airports, downtown districts or theme parks. It can be consider as similar system to the GRT as they have similar capacity, size and operating procedures. In this project, an active APM vehicle will be taken as reference for GRT vehicle design parameters.



Fig 4.1 Mitsubishi Crystal Mover on the Sengkang and Punggol LRT

The Mitsubishi Crystal Mover (C810) is an automated people mover (APM) vehicle for airports and light rail applications manufactured by Mitsubishi Heavy Industries [33]. This model of vehicle is used in, for instance, the Hong Kong International Airport Automated People Mover system. Taking the Crystal Mover as reference, the technical specifications of a GRT vehicle is designed as follow:

Maximum speed:	80 km/h	= 22.222 m/s
Operating speed:	40 km/h (Regional)	= 11.111 m/s
	70 km/h (Trunk)	= 19.444 m/s
	35 km/h (Coupling)	= 9.722m/s
Acceleration:	5 km/h/s	= 1.389m/s ²
Deceleration:	5 km/h/s	= 1.389m/s ²
Vehicle length:	8 m	
Width:	2.7 m	
Doors:	2 m wide, 2 per car	
Capacity:	30 passengers (Service)	
	45 passengers (Maximum)	

Simulation Flow Chart

Here is the flow of finding the values and expressions representing the behavior and performance of the GRT system under various assumptions:

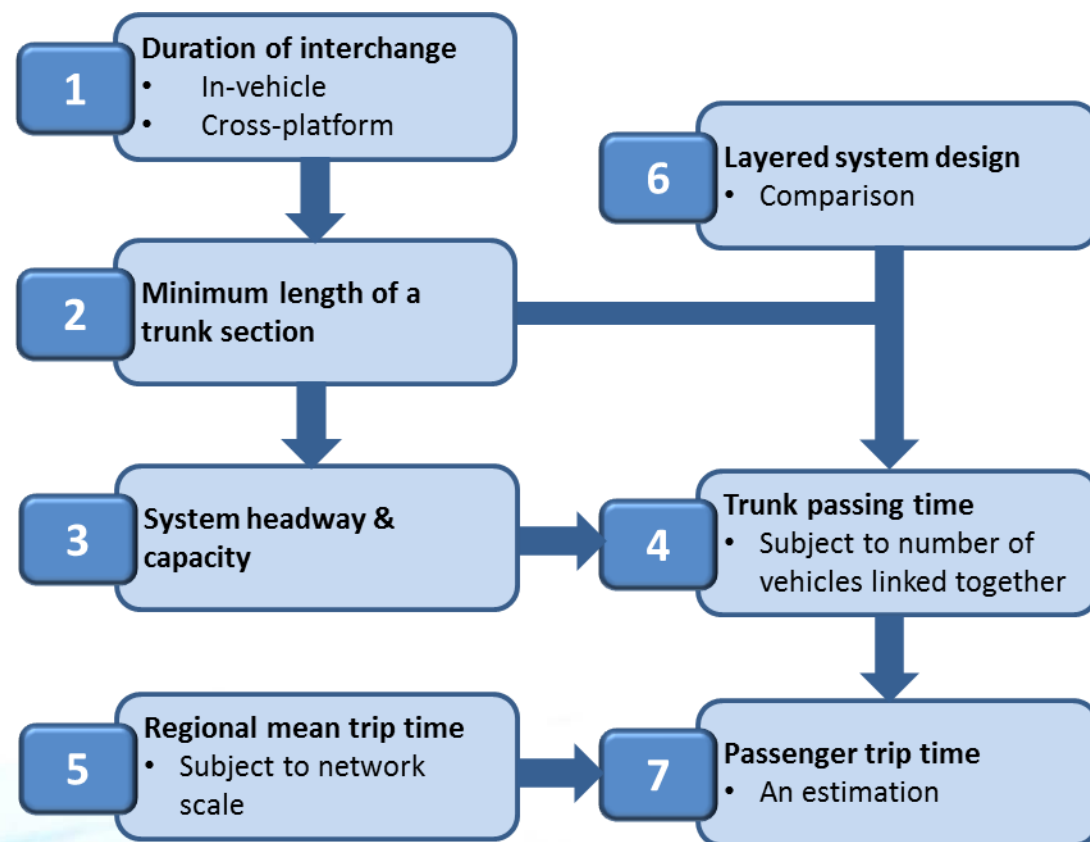


Fig 4.2 Simulation Flow Chart

4.1 The Passenger Movement

In an automated transportation system, despite nearly all the machines can be of centralized control, random human behavior contributes to the major unexpected variations on the total trip time. In the GRT system, the most direct source of delay will be caused by the interchange movements of passengers. Due to the implementation of in-vehicle interchange in this project, we have to know how much time is needed for interchange movements inside the vehicles. Besides, we want to know the efficiency and behavior of in-vehicle interchange, compared to the cross-platform interchange.

SUMO – the Traffic Simulation Software

SUMO (Simulation of Urban MObility) is an open traffic simulation suite developed by the Institute of Transportation Systems, German Aerospace Center [34]. It allows modelling of intermodal traffic systems, included with a wealth of supporting tools which handle tasks such as route finding, visualization and network import. SUMO was used to provide traffic forecasts for authorities of the City of Cologne during the Pope's visit in 2005 and during the Soccer World Cup 2006.

The merit of choosing SUMO outweighing the other simulation tools is the embedded module for human objects (passengers, pedestrians, etc.). A human object is able to move through the simulation network by walking, or even interacting with other transport modes such as transit vehicles. The walking behavior is calculated by embedded mathematical pedestrian model, simulating with higher degree of realism. Although SUMO programs need to be written in command line interface, it provides a tool called “GUISIM” which converts text syntax into animation. The passenger movements can then be observed through this animation.

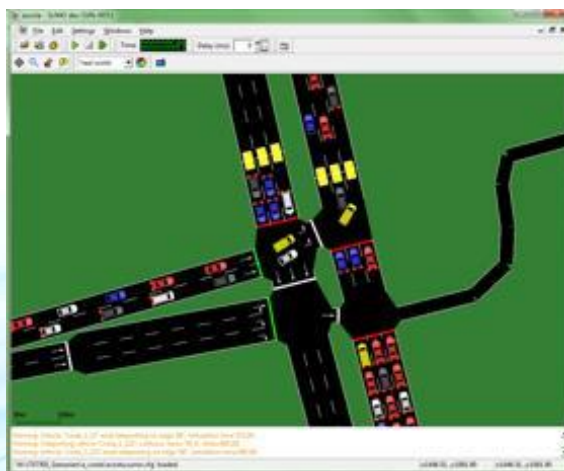


Fig 4.3 The SUMO animation

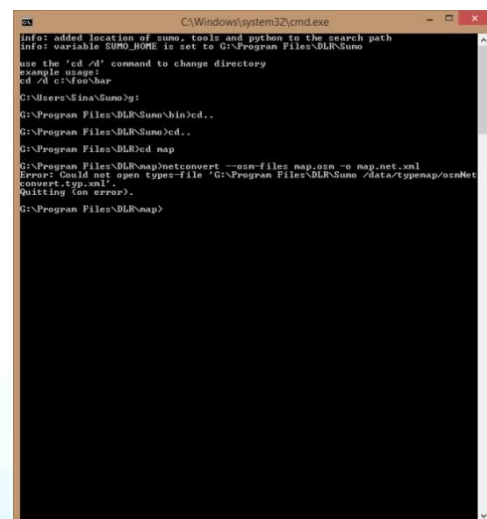


Fig 4.4 SUMO Command line

Assumptions

Assume a vehicle picks 30 passengers in normal service. It is expected that 10 out of 30 passengers in each vehicle need to do the interchange. However, to determine the capacity serving peak demand, we assume all 30 passengers have to do the interchange in this part of simulation.

4.1.1 Passenger Movement in In-vehicle Interchange



Fig 4.5 Linkage door between two train cars

By simulating the movements of passengers interchanging between two vehicles, duration of interchange can be determined. For the coupling between two vehicles, of course, the wider the linkage, the larger space to accommodate moving passengers. They can then move faster with fewer conflicts, resulting in shorter interchange time. Yet, in this step, we should test the longest possible time for determining minimum system requirements in the later parts. We set the width of linkage to be as narrow as possible with acceptable conflicts of movements.

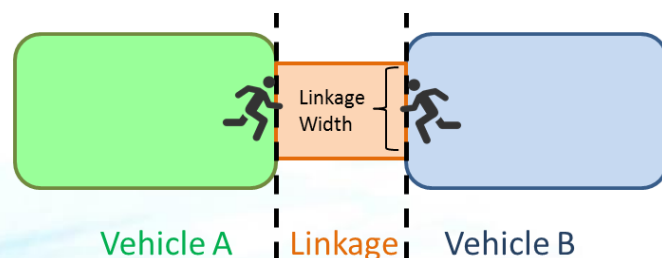


Fig 4.6 Diagram of linkage width

Using trial-and-error method, when linkage width larger than or equals to 1.3m, passengers (indicated as yellow arrows) from the two vehicles are able to pass through the linkage mutually with moderate conflict of movement.



Fig 4.7 Passengers can pass through with 1.3m wide linkage

However, if the linkage width is smaller than 1.3m, passengers from one vehicle have to stop and wait until all passengers from another vehicle passed the linkage.



Fig 4.8 Passengers in vehicle B stuck with <1.3m linkage

From the above simulations, using linkage width of 1.3m, the duration of in-vehicle interchange of 30 passengers is **22.4 seconds**.

4.1.2 Passenger Movement in Cross-platform Interchange

We have to conduct simulations observing the passenger movement in cross-platform interchange in order to determine its time difference with in-vehicle interchange. In railway system, there are two possible platform orientations – the side platform and the island platform:

Side Platform

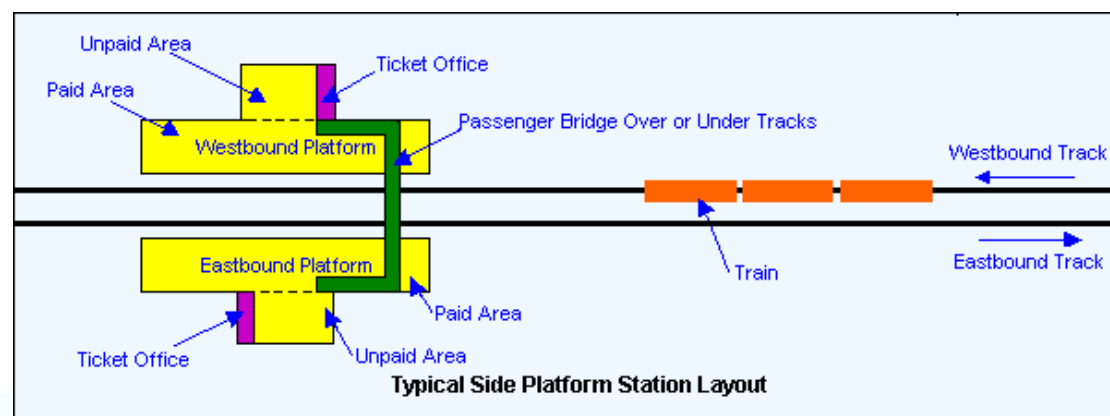


Fig 4.9 Side platform design

Platform is set on each side of an adjacent pair of tracks. As the pair of tracks is straight, besides having a lower construction cost, the side platform design facilitates pass through of trains in a higher speed or without deceleration. However, interchanging passengers from one platform have to climb up the footbridge to go to the other platforms.

Island Platform

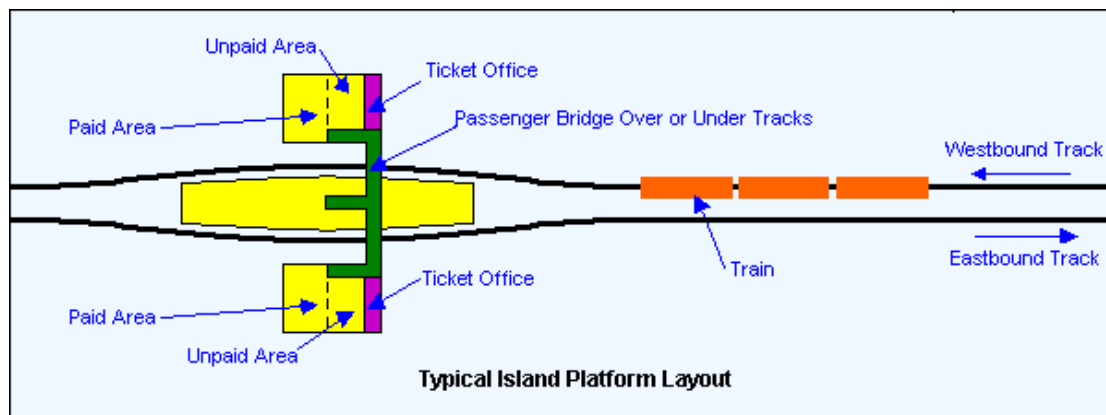


Fig 4.10 Island platform design

Platform is centered between the two tracks. Passengers can do the interchange easily walking on the same platform. However, bending of tracks cost higher, and trains have to enter the platform with lower speed than that of side platform design.

Considering the width of GRT vehicle of 2.7m, a width of 6m for two tracks, thus 6m long footbridge, is taken for side platform design. For island platform, 6m wide platform is also taken. In practice, the platform width is set above 2 times the vehicle width so as to accommodate two full vehicle-loads of passengers.

For the width of moving space, assume passenger boarding and alighting movements as fan-shaped – After exiting the vehicle A door, passengers want to walk into vehicle B through the shortest path – the middle line. However, facing the counter stream movement from vehicle B, passengers diverge, occupying more space for group movement avoiding conflict. In this simulation, considering 2m wide train door, assume the width of movement to be 2.6m. This width is also applied as the width in side platform footbridge.

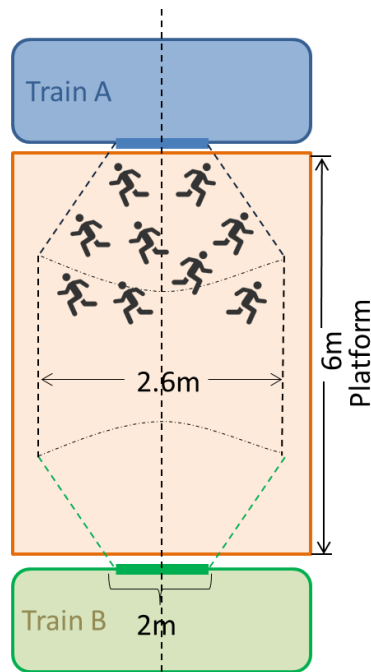


Fig 4.11 Assumed widths of fan-shaped movements

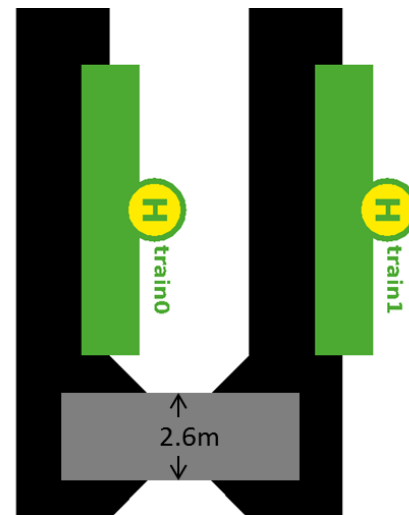


Fig 4.12 Model used in SUMO simulation

From the simulation animation, moderate crossflow (conflict of two head-to-head movements) can be observed. Some passengers are left behind the main stream because of these conflicts, and this results in longer total interchange time. Using the above settings, the simulation result shows that the duration of cross-platform interchange of 30 passengers is 23 seconds.

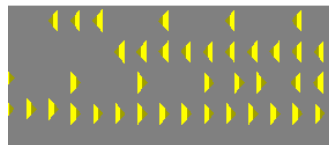


Fig 4.13 Two streams of passengers pass through with moderate conflicts



Fig 4.14 Near the end of simulation, some passengers are left behind due to the conflicts

Comment

Although the total interchange time of in-vehicle interchange is just close to that of cross-platform interchange, the effects of the two approaches onto the whole running operation of the vehicle should be further evaluated.

4.2 Modes of Coupling

In in-vehicle interchange, two vehicles couple with each other when riding on the truck section. Sufficient time should be provided so that all passengers can successfully change to their destination vehicle before splitting. As the vehicles continue running in interchange, the trunk section should be of enough length. By finding the total time needed for the whole coupling process, we can deduce the minimum length needed for the trunk section. For the coupling, two possible scenarios can happen in the GRT system:

4.2.1 Coupling with Decelerated Speed

To minimize delay, the coupling should be conducted without stopping. This can be done by facilitating an accurate coordination of the two vehicles.

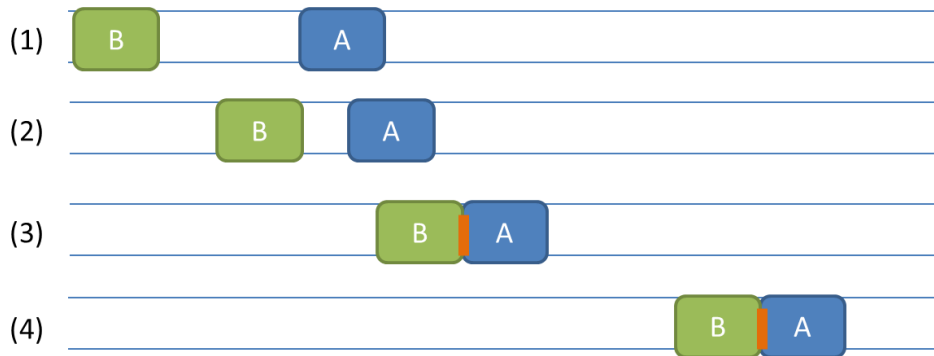


Fig 4.15 Stages of operation of decelerated coupling (see the following paragraph)

Let the leading vehicle be vehicle A and the following vehicle be vehicle B.

- (1) After the two vehicles are instructed to couple, vehicle A decelerates from normal speed (70km/h) to coupling speed (35km/h).
- (2) Vehicle B continues to run at normal speed for a while, catching up the decelerated vehicle A.
- (3) When approached, vehicle B decelerates to coupling speed and couple with vehicle A.
- (4) After coupling, the combined vehicle accelerates back to normal speed.

The whole process can be represented by the following distance-time graph, and the related calculations are attached as below:

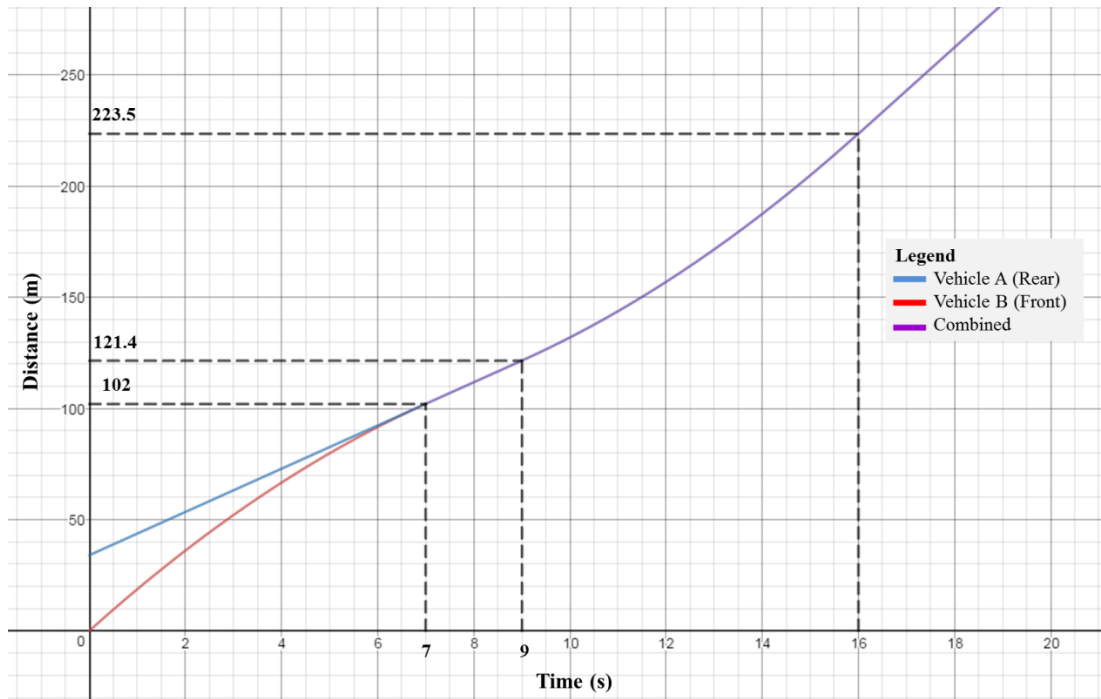


Fig 4.16 S-t graph of the two vehicles with decelerated coupling

Time for vehicle B decelerates to coupling speed

$$t = \frac{v - u}{a} = \frac{9.722 - 19.444}{-1.389} = 7 \text{ seconds}$$

The two vehicles meet after vehicle B has travelled for

$$s = ut + \frac{1}{2}at^2 = 19.444 \times 7 + \frac{1}{2} \times -1.389 \times 7^2 = 102 \text{ meters}$$

Assume there is 2 second buffering time after coupling.

$$s = 102 + vt = 102 + 9.722 \times 2 = 121.44 \text{ meters}$$

In other words, the linkage door opens at $t = 9$ seconds. As acceleration and deceleration are equal, it takes 7 seconds for the combined train to accelerate from coupling speed back to normal speed. Vehicle B has travelled for

$$s = 121.44 + \frac{v^2 - u^2}{2a} = 121.44 + \frac{19.444^2 - 9.722^2}{2 \times 1.389} = 223.51 \text{ meters}$$

From part 1.1, the linkage door opens for at least 22.4 seconds. Thus, the vehicles run at free-flow for $22.4 - 7 = 15.4$ seconds after accelerated back to the normal speed.

$$s = 223.51 + vt = 223.51 + 19.444 \times 15.4 = 523 \text{ meters}$$

Therefore, for the decelerated speed coupling scenario, at least 523 meters of trunk section should be provided. The total time for the whole coupling process is 31.4 seconds.

4.2.2 Coupling after Stopped

Besides the decelerated coupling technique, there is also possibility that two vehicles separate a longer distance with each other, and the leading vehicle has to stop and wait for the following vehicle. Another possible situation is that the truck is congested, so that the two vehicles have to couple after stopped.



Fig 4.17 Stages of operation of stopped coupling (see the following paragraph)

- (1) After the two vehicles are instructed to couple, vehicle A stops to wait for coupling.
- (2) Vehicle B decelerates from normal speed (70km/h) to nearly zero speed, and couple with vehicle A.
- (3) After coupling, the combined vehicle accelerates back to normal speed.

The whole process can be represented by the following distance-time graph, and the related calculations are attached as below:

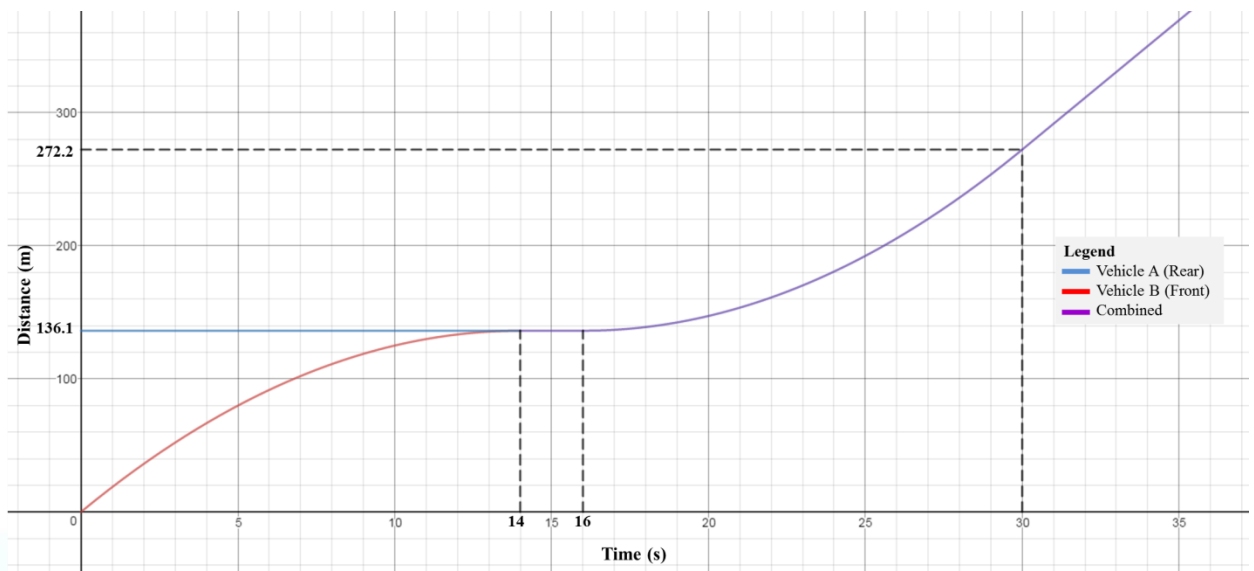


Fig 4.18 S-t graph of the two vehicles with stopped coupling

The time needed for vehicle B to decelerate from normal speed to zero

$$t = \frac{-u}{a} = \frac{-19.444}{-1.389} = 14 \text{ seconds}$$

and vehicle B has travelled

$$s = \frac{v^2 - u^2}{2a} = \frac{0 - 19.444^2}{2 \times -1.389} = 136.1 \text{ meters}$$

Assume a 2 second buffering time for the coupling. Linkage door opens at $14 + 2 = 16$ seconds. Then, the combined vehicle accelerates to normal speed.

$$s = 136.1 + \frac{v^2 - u^2}{2a} = 136.1 + \frac{19.444^2}{2 \times 1.389} = 272.2 \text{ meters}$$

and this acceleration takes 14 seconds. From part 1.1, the linkage door opens for at least 22.4 seconds. Thus, the vehicles run at free-flow for $22.4 - 14 = 8.4$ seconds after accelerated back to the normal speed.

$$s = 272.2 + vt = 272.2 + 19.444 \times 8.4 = 435.5 \text{ meters}$$

Therefore, for the stopped coupling scenario, at least 435.5 meters of trunk section should be provided. The total time for the whole coupling process is 38.4 seconds.

Comment

We take **523m**, the longer length calculated from the above two scenarios, as the minimum length of the trunk section. Considering the random human behavior, it is possible to take longer than 22.4s for finishing the interchange. It is suggested that the actual trunk section should be of much longer length ($\gg 523\text{m}$) dealing with unexpected disturbance.

4.3 Simulation on Trunk Operation and Capacity Calculation

In current railway system, trains from different routes are gathered to a major hub station/terminal. Passengers from these routes alight from the original trains and shift to their destination trains across the platforms. Now, the inspiration of in-vehicle interchange aims at minimizing passenger delay by running the train and doing the interchange at the same time. With this new approach, trains do not need to stop at platform, or even no need to set the specific interchange point.

From part 1, we found the duration of passenger movement in in-vehicle interchange can be close to that of cross-platform, but how about the effect of starts-and-stops of trains onto the whole interchange operation? In the following simulations and calculations, the behaviors of two vehicles running on a 1km straight section, with in-vehicle and cross-platform interchange respectively, will be studied.

Scenario and Assumptions

In this part, the total time for the two vehicles running over a 1km straight section will be evaluated.

For cross-platform scenario, each vehicle will run on one of a pair of 1km tracks. Station 1, which is an interchange station, is set at the beginning point of the section. The two vehicles will enter Station 1 while decelerated from normal speed (70km/h). 30 passengers from each vehicle alight and walk to the adjacent platform to board another vehicle. Station 2, a normal station, is set at the end point of the section. The counting starts when the two vehicles enter the starting point; and the counting ends after the two vehicles have arrived Station 2.

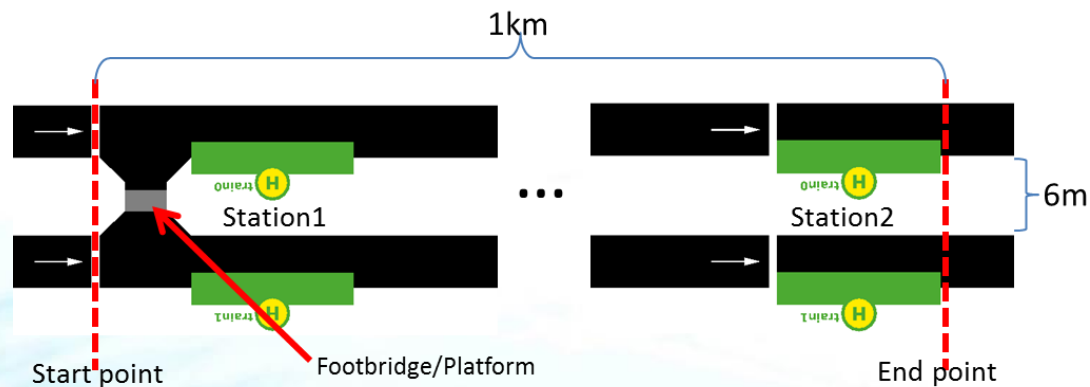


Fig 4.19 Indications for simulation network of cross-platform interchange

In addition, the station dwell time of the vehicles will be taken into account. The determining factors are:

- T1: Door open time
- T2: Passenger alighting time
- T3: Passenger boarding time
- T4: Door close to vehicle starts

In this part, $(T2 + T3)$ is summed as the interchange time (23 seconds). Assume T1 is 2 seconds and T4 is 5 seconds.

For in-vehicle interchange, the setting is the same except the two vehicles will run on a single 1km straight track. Assume using “coupling with decelerated speed”, the leading vehicle enters the section at coupling speed (35km/h) while the following vehicle enters at normal speed (70km/h). Then, the two vehicles couple together and arrive to Station 2. Some values calculated in part 2 will be put into reuse.

4.3.1 Trunk Operation with Cross Platform Interchange

The screen captures of the simulation and descriptions are as follow:

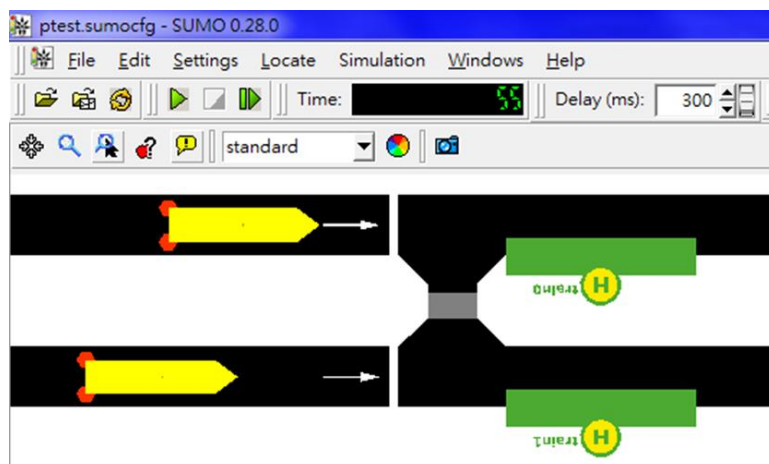


Fig 4.20 When time = 55 seconds, the vehicles enter the section

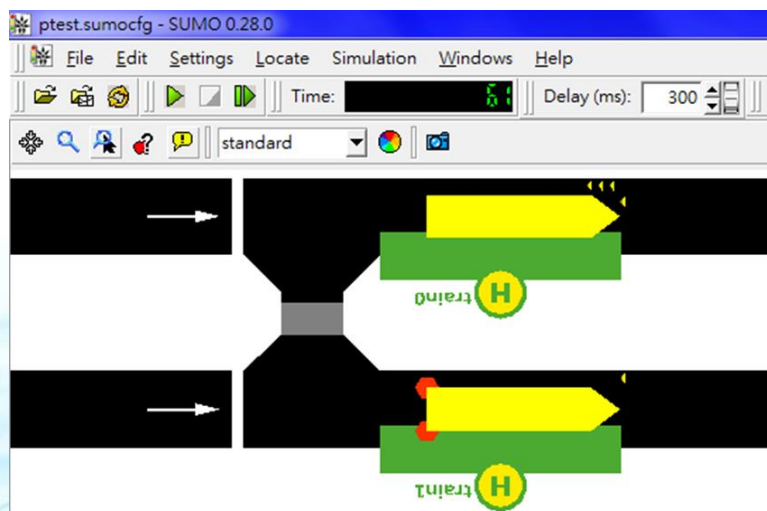


Fig 4.21 When time = 61 seconds, passengers alight at Station 1

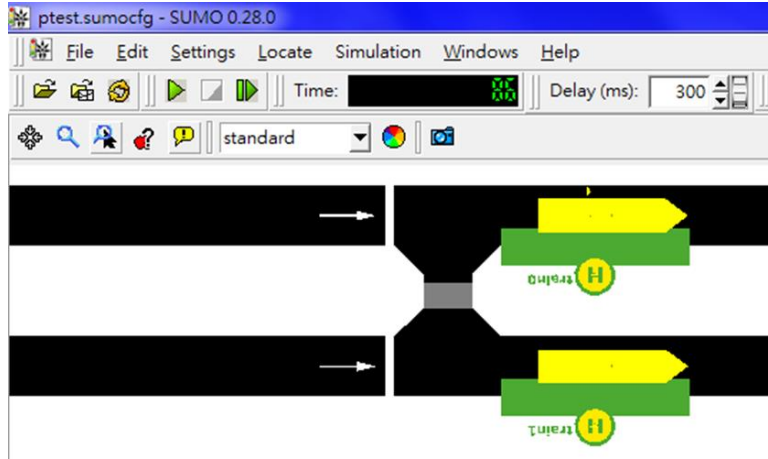


Fig 4.22 When time = 85 seconds, all passengers boarded the vehicles

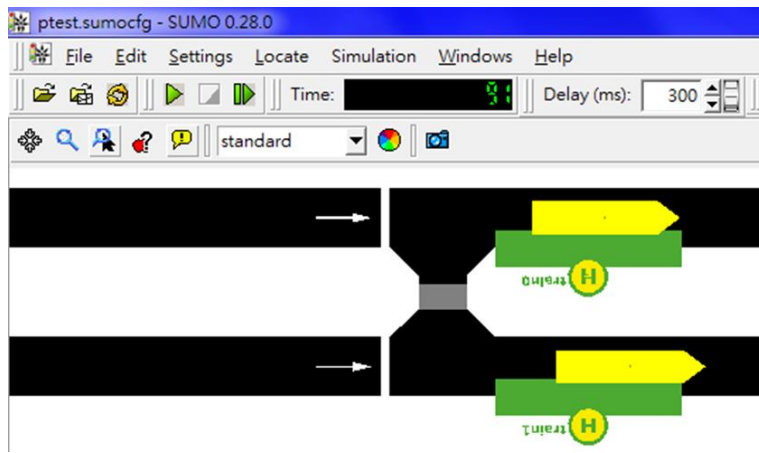


Fig 4.23 When time = 91 seconds, vehicles start

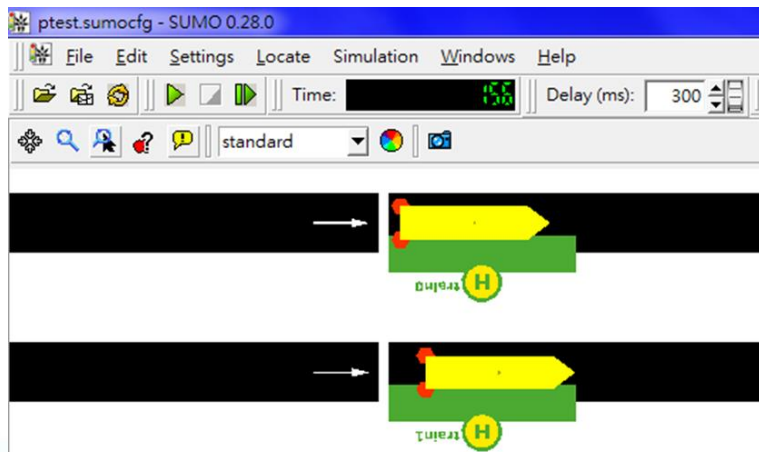


Fig 4.24 When time = 157 seconds, vehicles arrive Station 2

From the above simulation, the total travel time for the two vehicles running through a 1km section using cross-platform interchange is $157 - 55 = 102$ seconds. In here, we can deduce the minimum headway and capacity of this arrangement by the minimum theoretical station headway equation [3]:

$$h_s(\text{min}) = T_{\text{dwell}} + \left(\frac{2NL}{a_n}\right)^{1/2} + \left(t_r + \frac{v}{2d_f} - \frac{v}{2d_l} + \frac{NL + x_0}{v}\right)$$

where $h_s(\text{min})$ = Minimum theoretical headway (sec)
 T_{dwell} = Station dwell time (sec)
 N = Number of car per train, = 1 in this case
 L = Length of a car, = 8m in this case
 a_n = Acceleration of the train, = 1.389m/s^2 in this case
 t_r = Driver's reaction time, = 0 as automated system
 v = Normal train speed, = 19.444m/s in this case
 d_f = Deceleration rate of the leading train, = 1.389m/s^2
 d_l = Deceleration rate of the following train, = 1.389m/s^2
 x_0 = Safety margin after stop, = 0 as automated system

From the simulation and assumption, station dwell time is

$$T_{\text{dwell}} = T1 + (T2 + T3) + T4 = 2 + 24 + 5 = 31 \text{ seconds}$$

Subbing the values into the equation:

$$h_s(\text{min}) = 31 + \sqrt{\frac{2 \times 8}{1.389}} + \frac{8}{19.444} = 34.8 \text{ seconds}$$

Then, we use the passenger capacity equation to get the capacity of this arrangement:

$$C_{\text{pass}} = \frac{3600Nn}{h}$$

where C_{pass} = Passenger capacity (pax/hr)
 n = Number of passenger per car, = 30 in this case
 N = Number of car per train, = 1 in this case
 h = Calculated headway (sec)

$$C_{\text{pass}} = \frac{3600 \times 30}{34.8} = 3103.45 \text{ pax/hr}$$

4.3.2 Trunk Operation with In-vehicle Interchange

First, we use the theoretical station headway equation to get the theoretical minimum headway of the trunk section:

$$h_s(\text{min}) = \sqrt{\frac{2 \times 8}{1.389}} + \frac{8}{9.722} = 4.22 \text{ seconds}$$

The station dwell time (T_{dwell}) is set to zero as the vehicles do not stop within the whole operation. Vehicle speed (v) is set to 35km/h instead of 70km/h as the former is slower.

Next, we are going to calculate the actual headway, considering the whole operation in step-by-step manner. Let the leading vehicle be vehicle A and the following vehicle be vehicle B.

Time and distance for vehicle B decelerates from normal speed to coupling speed

$$t = \frac{v - u}{a} = \frac{9.722 - 19.444}{-1.389} = 7 \text{ seconds}$$

$$s = ut + \frac{1}{2}at^2 = 19.444 \times 7 + \frac{1}{2} \times -1.389 \times 7^2 = 102 \text{ meters}$$

In 7 seconds, vehicle A can travel a distance of

$$s = vt = 9.722 \times 7 = 68 \text{ meters}$$

Before vehicle B decelerates, gap between front of vehicle A and front of vehicle B has a distance of $102 - 68 + 8 = 42\text{m}$:

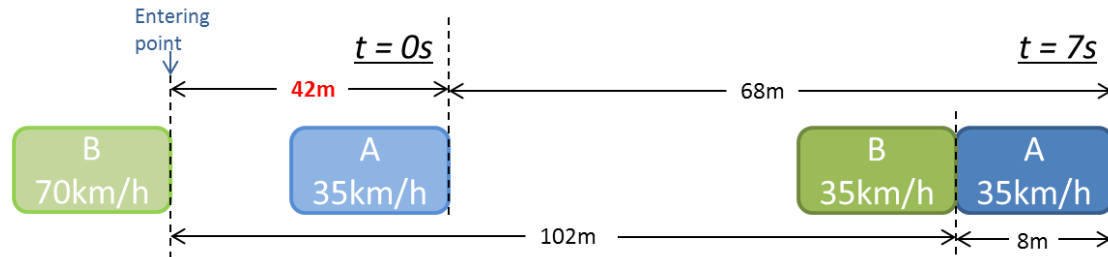


Fig 4.25 Vehicle locations and the important lengths

Time for vehicle A to travel this 42m

$$\frac{42}{9.722} = \mathbf{4.32 \text{ seconds}}$$

which means that vehicle A should enter the trunk section 4.32 seconds before vehicle B enters. Comparing with the theoretical minimum headway $h_s(\text{min})$ of 4.22 seconds, we should take the larger headway, 4.32 seconds, as the actual headway.

Assume 2 second buffering time after coupling. The combined vehicle travels for

$$s = vt = 9.722 \times 2 = 19.44 \text{ meters}$$

The deceleration distance and time from 70km/h to zero are

$$s = \frac{v^2 - u^2}{2a} = \frac{0 - 19.444^2}{2 \times -1.389} = 136.1 \text{ meters}$$

$$t = \frac{-u}{a} = \frac{-19.444}{-1.389} = 14 \text{ seconds}$$

Therefore, the combined train has a free-flow distance of

$$1000 - (102 + 19.44 + 102 + 136.1) = 640.46 \text{ meters}$$

and the free-flow time is $640.46/19.444 = 33$ seconds. The total time for the two vehicles to run through 1km trunk section is then

$$4.32 + 7 + 2 + 7 + 33 + 14 = 67.32 \text{ seconds}$$

Using the passenger capacity equation, the maximum capacity of the trunk section is

$$C_{\text{pass}} = \frac{3600 \times 30}{4.32} = \mathbf{25000 \text{ pax/hr}}$$

Comment

From the above simulations, the differences on total travel time and capacity of cross-platform interchange to in-vehicle interchange are

$$\text{Time ratio} = 102/67.32 = 151.5\%$$

$$\text{Capacity ratio} = 3103.45/25000 = 12.4\%$$

We can conclude that the mode of interchange can cause major difference on system behavior. In-vehicle interchange successfully enhances the performance of the system, increasing capacity and reducing time delay.

4.4 Multiple Couplings

In the previous simulations, we have studied the behavior of interchange between two vehicles. In this part, we will further study the influence acting onto the system outcome if more than two vehicles couple together for interchange.

First, we are going to observe the passenger movement between 3 vehicles – vehicle A, B and C. Assume each vehicle has 30 passengers. Taking vehicle A as example, assume 15 passengers in vehicle A go to vehicle B and another 15 passengers go to vehicle C.



Fig 4.26 Simulation of passenger movement in 3 vehicles

The duration of the simulation is 48 seconds. Comparing with the duration of 2 vehicles, we can deduce that total duration of interchange can be roughly computed by $24(N - 1)$, where N is the number of vehicles coupled.

In addition, it is found that the minimum feasible width of linkage is equal to the vehicle width. For coupling more than 2 vehicles, it is suggested that sufficient linkage space should be provided.

4.4.1 Effect on Trunk Passing Time with Multiple Couplings

Next, the effect of multiple couplings onto the trip time will be studied. Let vehicle A be the leading vehicle, vehicle B be the vehicle following A, and vehicle C be the vehicle following B. Assume using the scenario of “Coupling with Decelerated Speed” introduced in part 2.1 is performed.

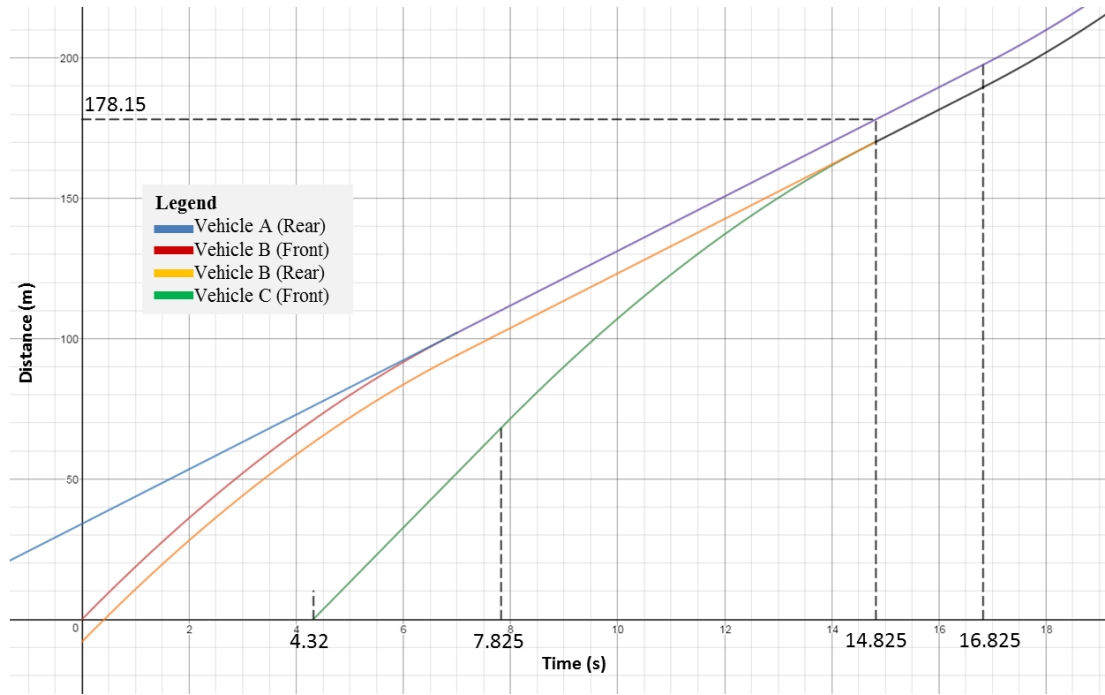


Fig 4.27 S-t graph for coupling operation of 3 vehicles

From Fig 16, we can find the equation representing the location of rear of vehicle A (the blue line) using graphical method:

$$s = 9.722t + 34.0235$$

After vehicle B joint vehicle A, the equation can be modified to represent the location of rear of vehicle B:

$$s = 9.722t + 34.0235 - 8 \quad \dots (1)$$

as vehicle length equals to 8 meters. From part 3.2, we have found that the headway of the trunk section is 4.32 seconds, which means vehicle C should pass the starting point 4.32 seconds later than vehicle B. Meanwhile, it takes 7 seconds and 102 meters for the vehicles to decelerate from normal speed (70km/h) to coupling speed (40km/h). We can imagine that after vehicle C passes the starting point, it keeps running at normal speed for a while, then decelerates to coupling speed and couples with vehicle B. Let u be the time when vehicle C starts decelerating. The equation can be written as

$$s = 19.444(u - 4.32) + 102$$

Let t' be the time when vehicle C couples with vehicle B. Then u can be subsidized as

$$s = 19.444(t' - 7 - 4.32) + 102 \quad \dots (2)$$

Solving (1) and (2), we have $t' = 14.825$ seconds and $u = 7.825$ seconds.

To summarize, Vehicle C enters the starting point at 4.32 seconds. It runs at normal speed until 7.825 seconds then decelerate to coupling speed. It couples with

vehicle B at 14.825 seconds. Assume 2-second coupling buffering time, the combined vehicle accelerates back to normal speed at 16.825 seconds.

Compare with 7 seconds and 102 meters in Fig 16, 7.825 seconds of additional time and 76.15 meters of additional distance are needed for increasing one coupling vehicle. Taking part 3.2 as reference, we can write the expression of total time passing the trunk section for the coupled GRT vehicles:

$$T = \frac{L_t - 76.15N - 223.44}{19.44} + 7.825N + 20.32$$

$$= \frac{L_t}{19.44} + 3.908N + 8.826$$

where T = Total time passing the trunk (sec)
 Lt = Length of the trunk (m)
 N = Number of coupling vehicles - 2

4.4.2 Cross-3-Platform Interchange – A Comparison

In this part, the interchange operation in a trunk section will be simulated with 3 vehicles. Getting the total duration, we can have a brief idea about how the time of cross-platform interchange differs from that of in-vehicle interchange, when the number of coupling is considered as additional parameter.

Scenario and Assumptions

For cross-platform interchange, three 1km tracks are set in the trunk section, and each of the three vehicles will run on one of the tracks. Station 1, which is an interchange station, is set at the beginning point of the section. The three vehicles will enter Station 1 while decelerated from normal speed (70km/h). 30 passengers from each vehicle alight and walk to the adjacent platform to board the other vehicles. Station 2, a normal station, is set at the end point of the section. The counting starts when the three vehicles enter the starting point; and the counting ends after the three vehicles have arrived Station 2. In addition, station dwell time of the vehicles will be taken into account. Assume 2 seconds train door open time and 5 seconds train door close and vehicle starts time.

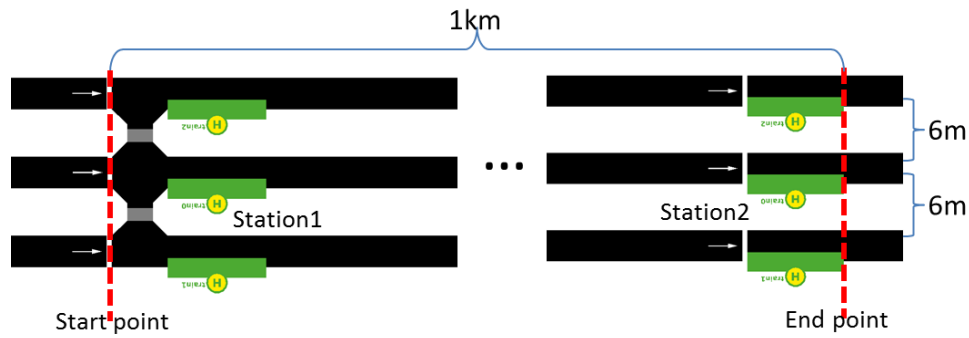


Fig 4.28 Indications for simulation network of cross-3-platform interchange

The screen captures of the simulation and descriptions are as follow:

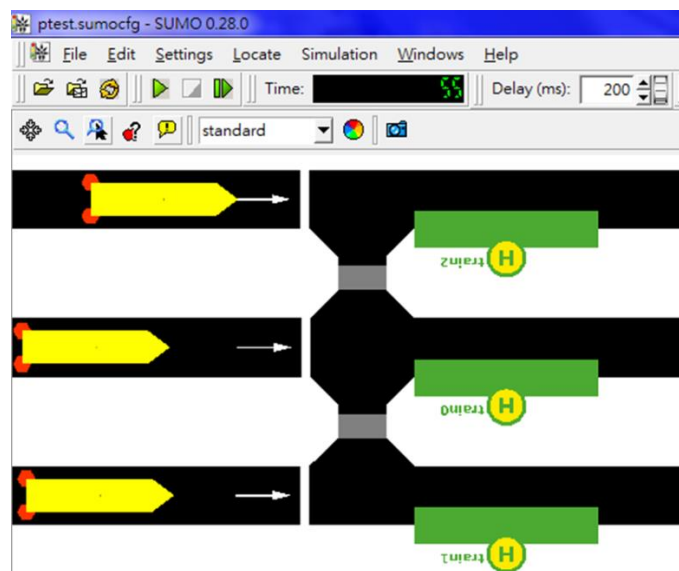


Fig 4.29 When time = 55 seconds, the vehicles enter the section

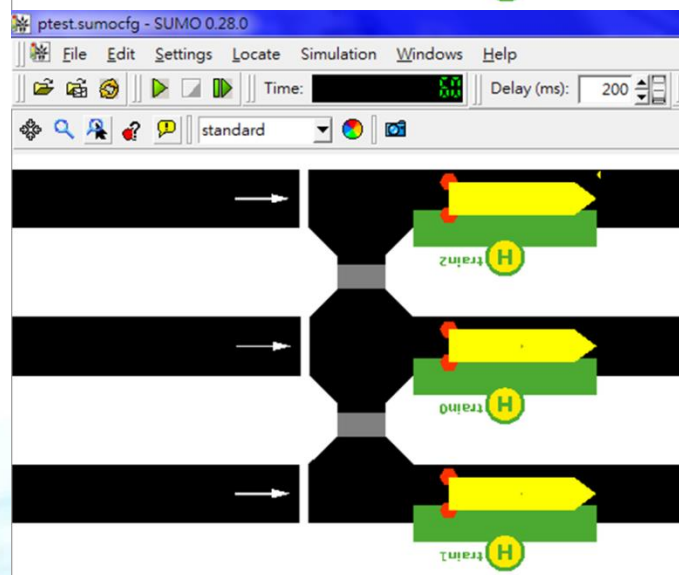


Fig 4.30 When time = 60 seconds, passengers alight at Station 1

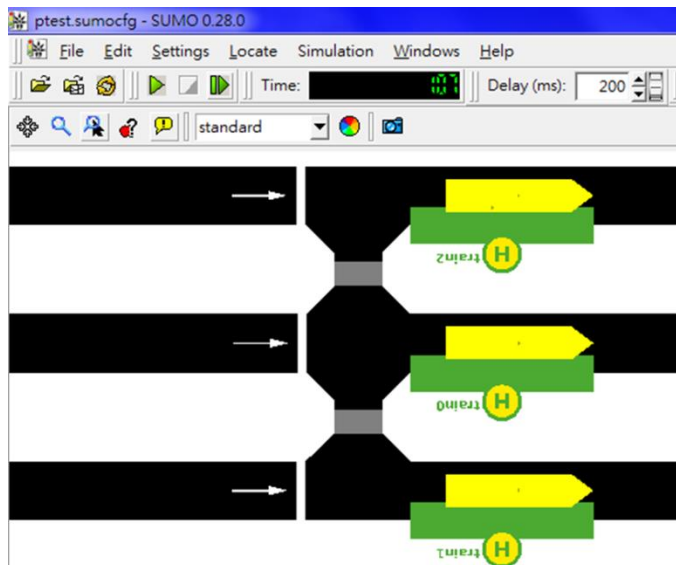


Fig 4.31 When time = 108 seconds, all passengers boarded the vehicles

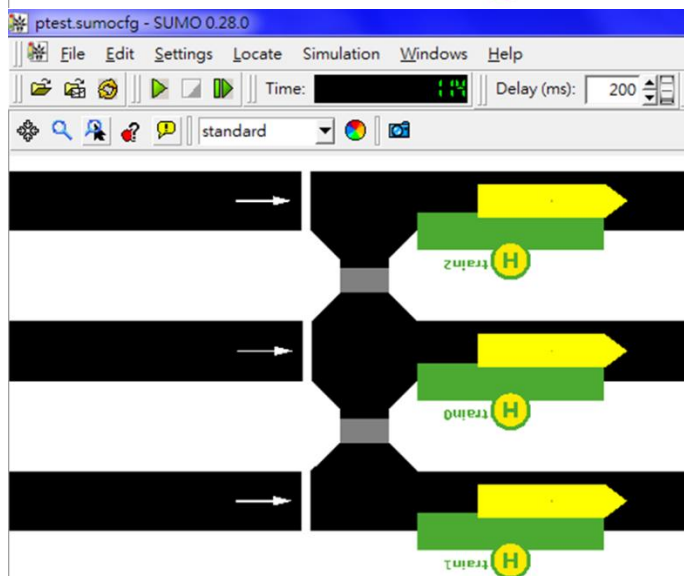


Fig 4.32 When time = 114 seconds, vehicles start

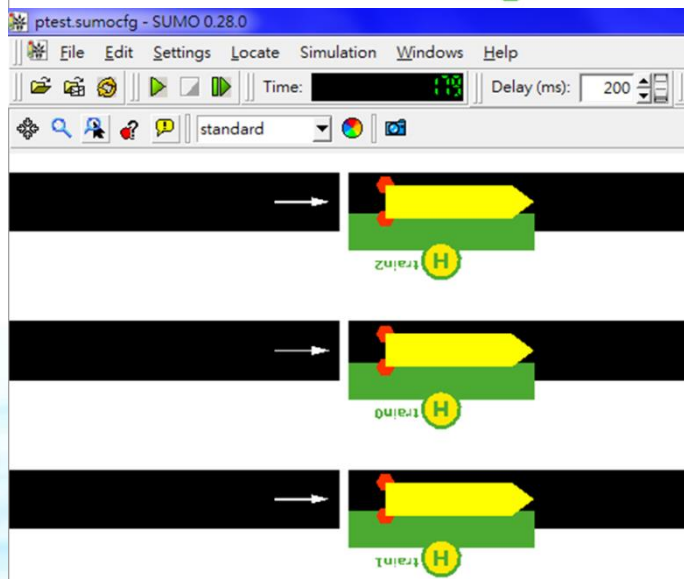


Fig 4.33 When time = 179 seconds, vehicles arrive Station 2

From the above simulation, the total travel time for the three vehicles running through a 1km section using cross-platform interchange is $179 - 55 = 124$ seconds.

From the simulation and assumption, station dwell time is

$$T_{\text{dwell}} = 2 + 48 + 5 = 55 \text{ seconds}$$

Subbing the values into the headway equation:

$$h_s(\text{min}) = 55 + \sqrt{\frac{2 \times 8}{1.389}} + \frac{8}{19.444} = 58.8 \text{ seconds}$$

Then, we use the passenger capacity equation to get the capacity of this arrangement:

$$C_{\text{pass}} = \frac{3600 \times 30}{58.8} = 1836.73 \text{ pax/hr}$$

Comment

From the above station dwell time, we found that the 48 seconds are needed for passenger interchange among three vehicles. This has proven the duration of interchange relates to the number of coupling vehicles by $24(N - 1)$, where N is the number of vehicles coupled.

In this part, the differences on total travel time and capacity of cross-platform interchange to in-vehicle interchange are

$$\text{Time ratio} = 124/67.32 = 184.2\%$$

$$\text{Capacity ratio} = 1836.73/25000 = 7.35\%$$

The values of total travel time and capacity become worse with increasing number of coupling vehicles. For larger number of platforms in an interchange station, some passengers may have higher chance to cross more platforms. For instance, for a station with 10 platforms, some passengers may only need to cross 2 platforms but others may need to cross 10 platforms. This can explain how the system performance and multiple couplings relate.

To conclude, using in-vehicle interchange with a sufficient length of trunk, the effect of multiple couplings can largely be eliminated. This is just what we have discussed in the first paragraph of part 3 - the esthetics of GRT system with in-vehicle interchange.

4.5 Junctions and Scale of Network

In a transportation system, conflicts of traffic happen mostly in junctions. Yet, these conflicts cannot be totally avoided but can only be minimized using signal coordination. Meanwhile, larger scale of network means more junctions, making avoidance of conflicts more difficult. In the GRT system, although automation is implemented in order to eliminate delay caused by random driver behaviors, reaction time and the induced fluid dynamics, delay can still occur in form of unutilized coordination among vehicles and over demand.

In the GRT system, the vehicles first collect passengers by circulating a *region*. Then, the vehicle goes onto the trunk section bounding to the other regions. In this part, we are going to test the maximum capacity that a *regional* network can hold while providing the acceptable level of service.

ATS Citymobil – a PRT Simulation Software

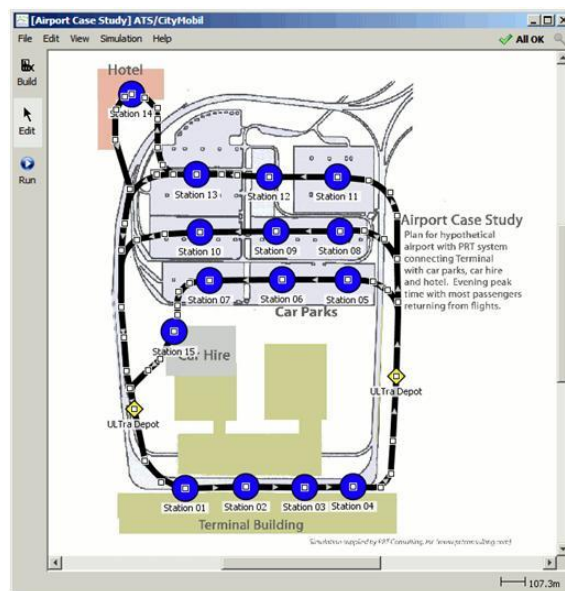


Fig 4.34 Interface of ATS Citymobil

The ATS Citymobil is a network design and simulation tool developed by the British engineering company ULtra Global PRT [35]. ULtra is a driverless automated personal rapid transit (PRT) or group rapid transit (GRT) system developed in the real world, and this software is specially designed for simulating the behavior of an ULtra system. It was used to aid the design and construction of the ULtra pod system in London's Heathrow Airport.

The merit of using ATS Citymobil outweigh the other tools is the utilized algorithm for automation. Besides accurate coordination on passing sequence and speeds, vehicles can accelerate at the same time and rate. Driver's reaction delay and safety gap between successive vehicles are set to zero.

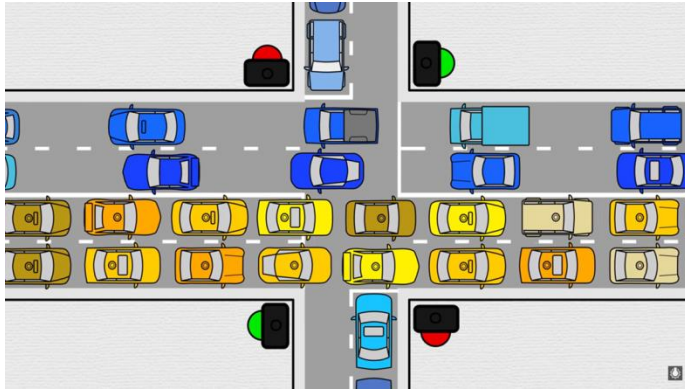


Fig 4.35 For eastbound traffic, as all vehicles react and accelerate at the same time, the gap between successive vehicles can be very small

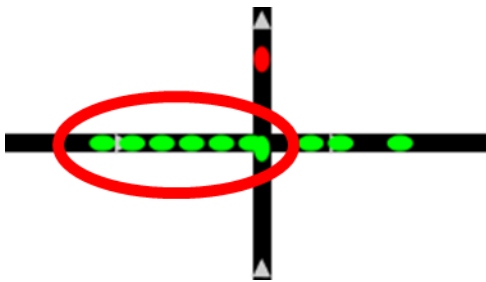


Fig 4.36 Situation described in Fig 35 can be observed in ATS Citymobil

ATS Citymobil allows setting the level of demand at each station and let the simulator construct an origin-destination demand matrix. Maximum capacity can then be test by trial-and-error. Status of individual vehicles can also be seen in the animation clearly by color indications.

Assumptions

In this part, we are going to observe the behavior of traffic inside a regional grid network. Assume the speed of vehicles running inside the regional network is 40km/h.

According to the Hong Kong Planning Standards and Guidelines (HKPSG) [36], a place is said to be accessible by railway if it is inside the 500m-radius catchment area of a rail station. As GRT system is expected to provide denser and more rapid services, assume grids of 500m*500m is used in constructing the network.

In the network, one-way system will be implemented. Instead of dual track, single track is used which allows movement of one direction only. The one-way system is simple to implement, no expensive capital outlay and excessive policing. It is effective in reducing conflicts in junctions; improving signal progression thus improved efficiency [32].

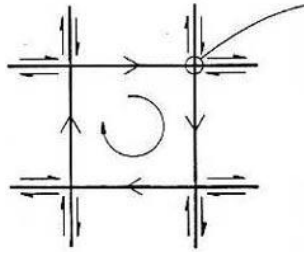


Fig 4.37 Layout of one-way system

The condition of junction is greatly affected by the travel demand from the peripheral stations. This is an unexpected factor except surveying the local environment in real situation. Therefore, in simulation, assume uniform demand among all stations.

Network with 6 Stations

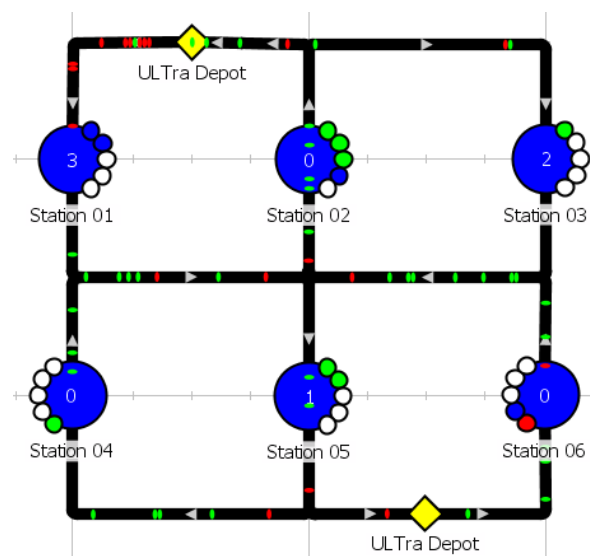


Fig 4.38 6-station network simulation

The first test network would be the arrangement used in the hardware model. An output table is displayed showing the results with 2 hours of simulation data:

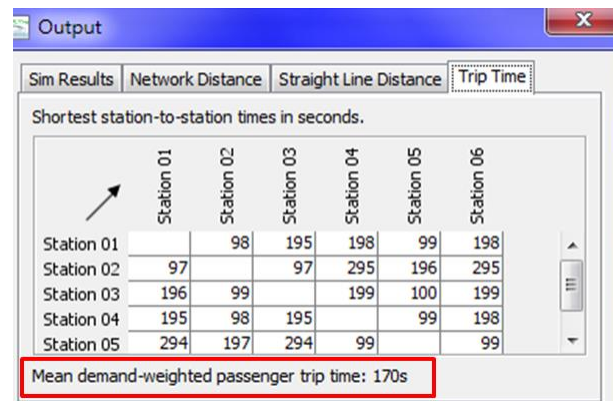
Output			
Sim Results	Network Distance	Straight Line Distance	Trip Time
Passenger waiting times by station (with 2.00 hours of simulation data):			
Station	Mean (s)	% <= 60s	N (groups)
Station 01	9	100	284
Station 02	9	98	318
Station 03	19	88	315
Station 04	21	86	302
Station 05	13	96	329
Station 06	5	100	282
Total	13	94	1830
Estimated fleet size: 86 vehicles.			

Fig 4.39 Result table of 6-station network simulation

The highlighted value is the number of group (vehicle) trips generated within the network for 2 hours. Therefore, the capacity of this network is

$$\frac{1830 \text{ veh} \times 30 \text{ pax/veh}}{2 \text{ hr}} = 27450 \text{ pax/hr}$$

and the network is capable for accommodating 86 running vehicles at the same time. In addition, the mean demand-weighted trip time per passenger is also calculated:



	Station 01	Station 02	Station 03	Station 04	Station 05	Station 06
Station 01		98	195	198	99	198
Station 02	97		97	295	196	295
Station 03	196	99		199	100	199
Station 04	195	98	195		99	198
Station 05	294	197	294	99		99

Mean demand-weighted passenger trip time: 170s

Fig 4.40 Trip time table of 6-station network simulation

The simulations for regional grid network with 9, 12 and 20 stations are also conducted. The results are summarized in the following table:

Stations	Capacity (pax/hr)	Fleet size	Mean trip time (s/pax)
9	40500	130	206
12	48600	167	218
20	73350	265	261

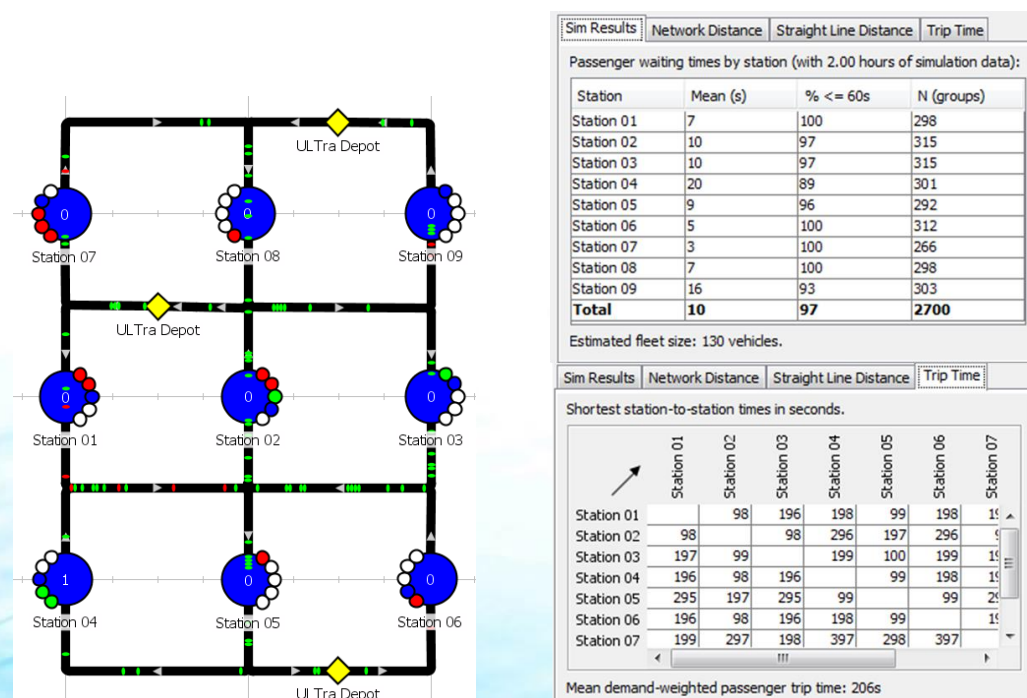


Fig 4.41 Results for 9-station network

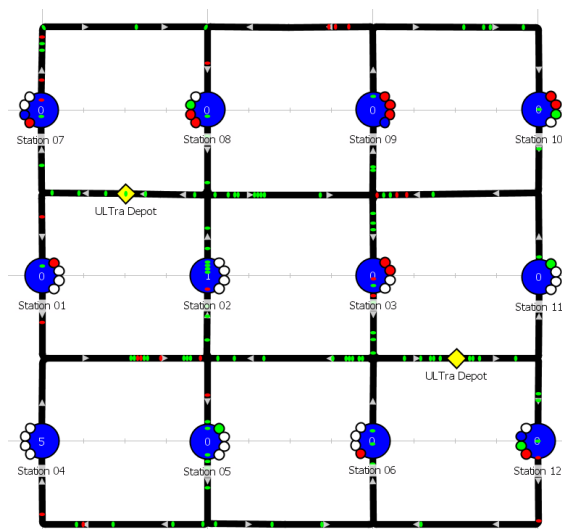


Fig 4.42 Results for 12-station network

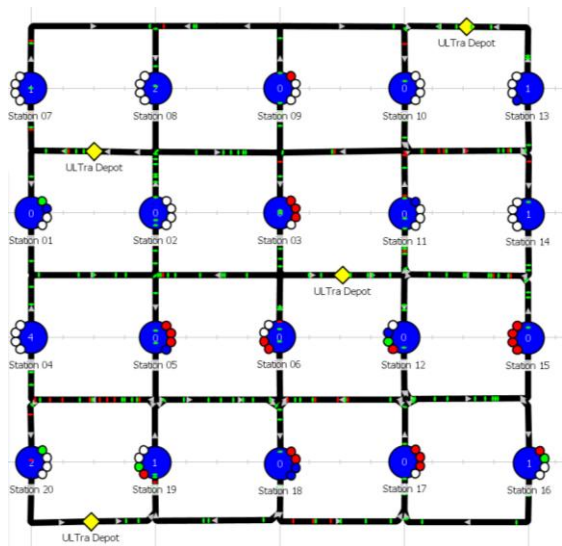
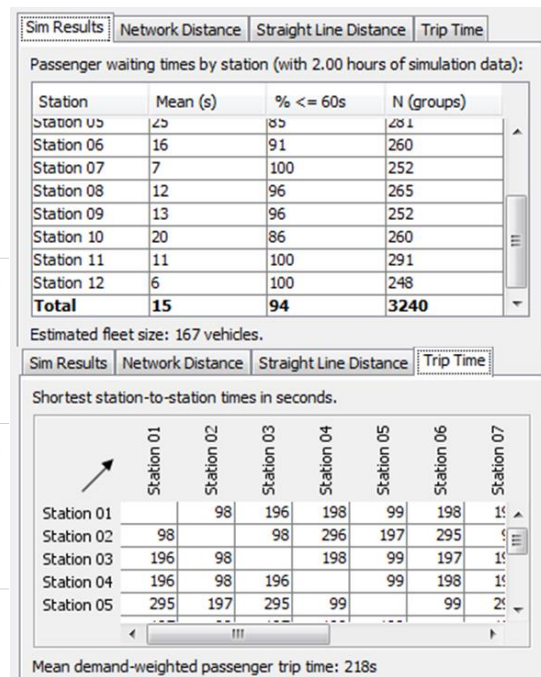
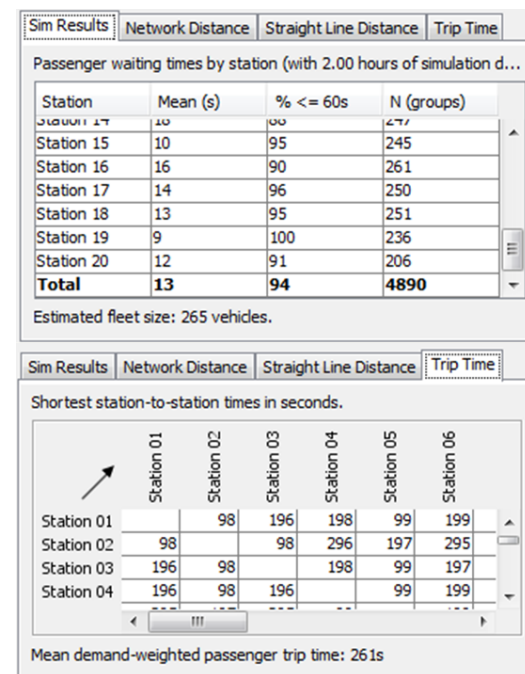


Fig 4.43 Results for 20-station network



Using the simulation results, the relationship between the size of a regional network and its performance is evaluated by regression analysis using Microsoft Excel.

SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0.99616276							
R Square	0.992340244							
Adjusted R Square	0.988510366							
Standard Error	2160.546746							
Observations	4							
ANOVA								
	df	SS	MS	F	Significance F			
Regression	1	1.21E+09	1.21E+09	259.1049	0.003837			
Residual	2	9335924	4667962					
Total	3	1.22E+09						
	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	8563.310345	2663.298	3.215303	0.08463	-2895.94	20022.56	-2895.94	20022.56
Stations	3334.931034	207.1806	16.09674	0.003837	2443.505	4226.357	2443.505	4226.357

Fig 4.44 Regression analysis table for capacity of a regional network

From the regression table, we can know that the generated expression is reasonable as the adjusted R square value tends to 1. The P-values of the variables are very small, showing that they are significant.

Therefore, the capacity of a regional grid network can be expressed as

$$\text{Capacity} = 8563x_1 + 3335x_2$$

Using regression analysis, the expressions for mean trip time and fleet size can also be found:

$$\text{Mean trip time (regional)} = 142x_1 + 6.1x_2$$

$$\text{Fleet size} = 13.3x_1 + 12.65x_2$$

$$\text{where } x_1 = \begin{cases} 1 & \text{when } x_2 \geq 2 \\ 0 & \text{otherwise} \end{cases}$$

$$x_2 = \text{Number of stations in a network}$$

SUMMARY OUTPUT									
Regression Statistics									
Multiple R	0.979241								
R Square	0.958912								
Adjusted R Square	0.938368								
Standard Error	9.316282								
Observations	4								
ANOVA									
	df	SS	MS	F	gnificance F				
Regression	1	4051.164	4051.164	46.6761	0.020759				
Residual	2	173.5862	86.7931						
Total	3	4224.75							
	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%	
Intercept	142.0345	11.48415	12.36787	0.006474	92.62219	191.4468	92.62219	191.4468	
Stations	6.103448	0.893363	6.831991	0.020759	2.259617	9.947279	2.259617	9.947279	

Fig 4.45 Regression analysis table for mean trip time of a regional network

SUMMARY OUTPUT					
Regression Statistics					
Multiple R	0.999322				
R Square	0.998644				
Adjusted R Square	0.997966				
Standard Error	3.438457				
Observations	4				
ANOVA					
	df	SS	MS	F	Significance F
Regression	1	17410.35	17410.35	1472.585	0.000678
Residual	2	23.64598	11.82299		
Total	3	17434			
Coefficients					
	Coefficients	Standard Error	t Stat	P-value	Lower 95% Upper 95% Lower 95.0% Upper 95.0%
Intercept	13.32874	4.238574	3.144628	0.087984	-4.90837 31.56585 -4.90837 31.56585
Stations	12.65287	0.329723	38.37427	0.000678	11.23419 14.07156 11.23419 14.07156

Fig 4.46 Regression analysis table for fleet size of a regional network

Comment

By comparing the calculated capacity, we can conclude that for each 6 stations a trunk section should be provided (recall: the capacity of the trunk was found to be 25000 pax/hr while the capacity of a 6-station regional network is 27450 pax/hr). In other words, there should be a dual trunk road connecting two regional network, while each of them has 6 stations.

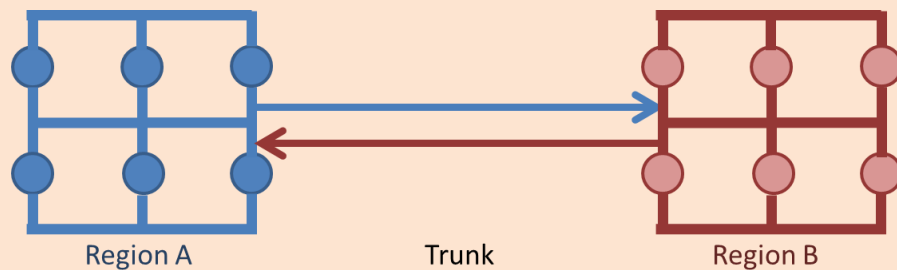


Fig 4.47 Configuration of two 6-station regional networks

For 12-station network, 2 trunks should be provided for each direction (recall: the capacity of a 12-station regional network is 48600 pax/hr, which is close to 2 times the capacity of a trunk):

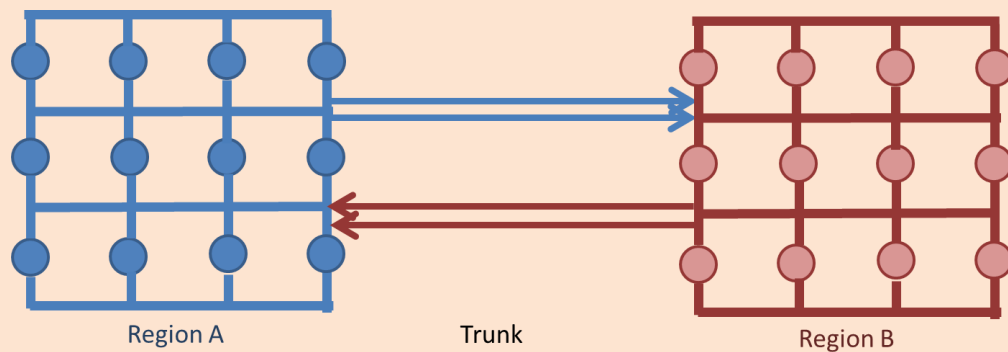


Fig 4.48 Configuration of two 12-station regional networks

4.6 Studies on Layered System

The GRT system is designed to have the right of way (ROW) of category A. Different from transportation systems of ROW category B and category C, the systems of category A can have a fully controlled right of way without grade crossings or any legal access by other vehicles or persons. The GRT system is then separated from mixed traffic, and the GRT tracks should be ran by GRT vehicles only.

To implement ROW category A, a system can be constructed in form of elevated system or underground system. Multiple layers of tracks within a system is possible, and the capacity can be increased by times. Indeed, building one more layer means doubling the cost. In balancing the two factors, it is suggested that the GRT system can have the following two layered designed:

Single Layer

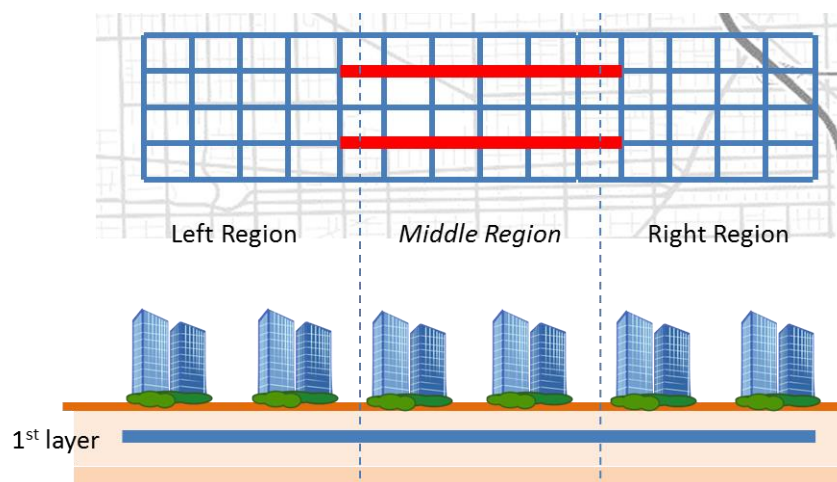


Fig 4.49 Single layer system with trunks highlighted in red

The whole GRT system is built on the same layer. Especially for underground system, the single layer design saves the cost as it is expensive to dig deeper the ground. However, junctions present on the trunk section if the trunk passes through a middle region (Fig 4.49). This may increase the chance of deceleration, thus average speed decreases.

Layered Trunk

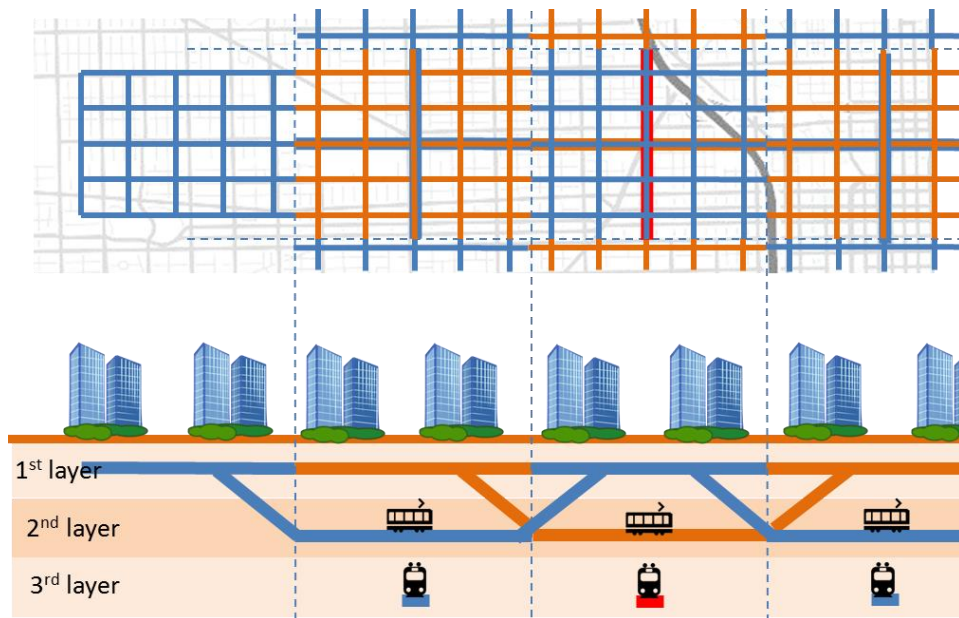


Fig 4.50 Multi-layer system with trunks on the deeper layers, 2nd layer for x-axis and 3rd layer for y-axis

Instead of putting all the things on the same layer, the trunk section is separated onto the next layer. Trunk can then operate smoothly without the disturbance of conflict. In configuration, “alternating region” technique can be used. Taking Fig 4.50 as reference, vehicles going from a blue region to another blue region can use trunk section on the second layer, while using the first layer if it goes from a blue region to a red region. Trunks laying on the x-axis should occupy the second layer, and trunks laying on the y-axis should occupy the third layer. Thus, for a system having regional network of N directions of trunks should have $(1+N)$ layers. This configuration can avoid forming intercepts of trunks. However, the cost of build such a layered system is high, as two more layers have to be built.

To evaluate the difference in performance between the two designs, and whether a single layer system is still capable for the operation, simulation is conducted using ATS Citymobil.

Assumptions

Assume a 2.5km truck section is built between two regions. For the case of single layer, an additional regional network is connected onto the middle of the trunk section.

The results are just used to evaluate the difference between the two layer designs, but have nothing to do with the expressions representing GRT system performance. Therefore, for simplicity, vehicles travel at 40km/h throughout the

network. No interchange action is performed and demands among stations are uniform.

Layered Trunk Design

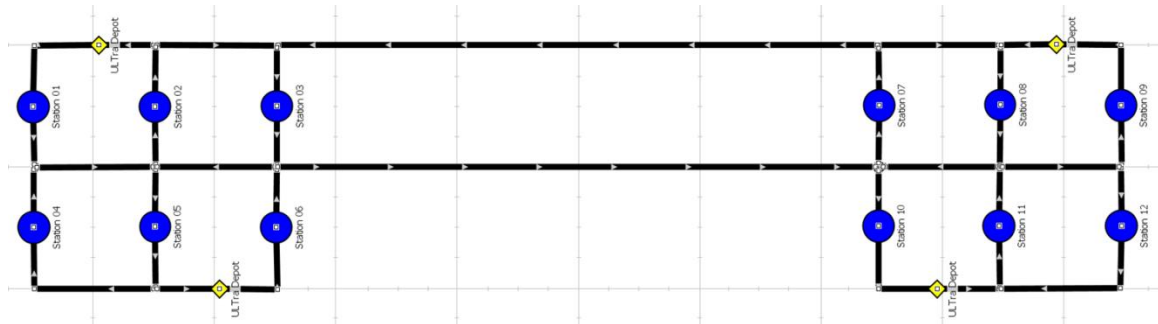


Fig 4.51 Simulation network for layered trunk design

Output			
Sim Results			
Network Distance			
Straight Line Distance			
Trip Time			
Passenger waiting times by station (with 2.00 hours of simulation data):			
Station	Mean (s)	% <= 60s	N (groups)
Station 01	12	100	242
Station 02	16	90	253
Station 03	35	73	242
Station 04	29	77	251
Station 05	17	92	246
Station 06	9	100	249
Station 07	12	94	217
Station 08	8	100	247
Station 09	18	89	255
Station 10	12	95	262
Station 11	13	99	267
Station 12	15	92	229
Total	16	92	2960

Fig 4.52 The result table of layered trunk design simulation

From Fig 4.52, we have the total number of group (vehicle) trips generated in this network. Therefore, the capacity per region is

$$\text{Capacity} = \frac{2960 \text{ veh} \times 30 \text{ pax/veh}}{2 \text{ hr} \times 2 \text{ regions}} = 22200 \text{ pax/hr/region}$$

which is quite close to the calculated capacity in the previous parts.

Single Layer Design

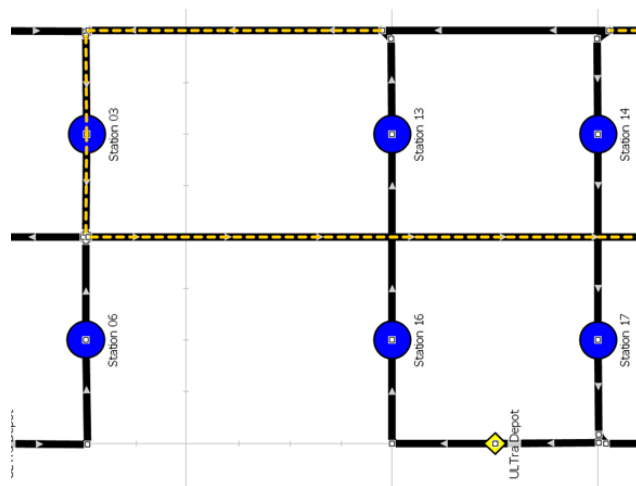


Fig 4.53 Yellow dotted line indicates over-capacity

When constructing the test network, interesting thing happened. Some of the tracks are highlighted by yellow dotted line, indicating over-capacity on those tracks. In other words, we can already know that the single layer design cannot handle the same level of demand tested on the layered trunk design! In spite of this, we still want to know how large is the difference, and the simulation continued after lowering the travel demand.

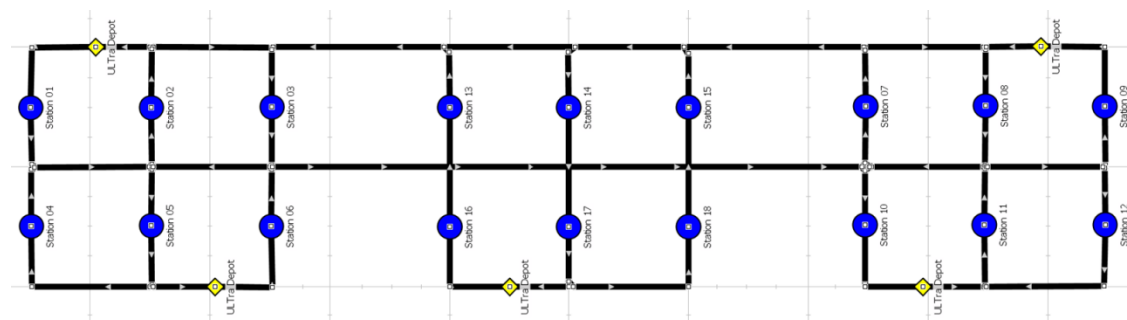


Fig 4.54 Simulation network for single layer design

Output			
Sim Results			
Network Distance			
Straight Line Distance			
Trip Time			
Passenger waiting times by station (with 2.00 hours of simulation data):			
Station	Mean (s)	% <= 60s	N (groups)
Station 01	15	100	131
Station 02	17	93	143
Station 03	14	94	129
Station 04	36	79	155
Station 05	14	94	122
Station 06	16	98	145
Station 07	29	81	129
Station 08	16	100	132
Station 09	26	77	135
Station 10	21	88	135
Station 11	15	100	130
Station 12	32	75	149
Station 13	27	82	140
Station 14	43	68	138
Station 15	53	59	144
Station 16	14	100	126
Station 17	27	88	121
Station 18	63	57	138
Total	27	85	2442

Fig 4.55 The result table of single layer design simulation

$$\text{Capacity} = \frac{2442 \text{ veh} \times 30 \text{ pax/veh}}{2 \text{ hr} \times 3 \text{ regions}} = 12210 \text{ pax/hr/region}$$

From the result above, we can know that the capacity of the single layer design is just 55% of that of layer trunk design. But, another thought comes out – how about adding one more trunk to the previous network? As the cost of building one more trunk may be compensable to that of building one in deeper layer.

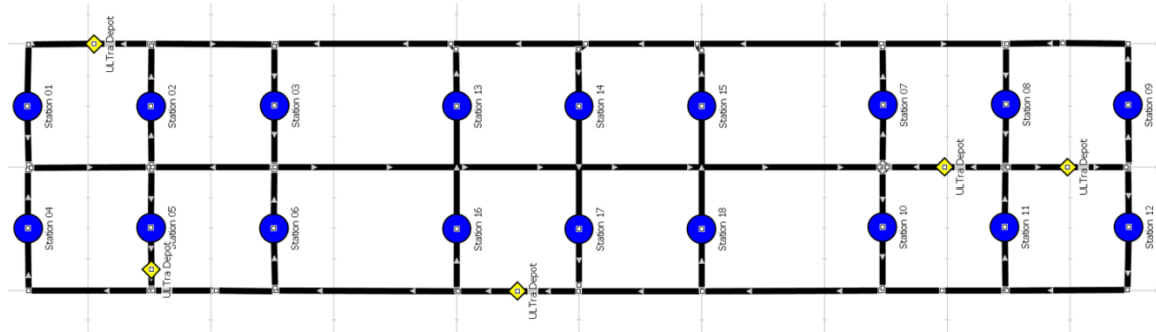


Fig 4.56 Simulation network for two-trunk single layer design

Output			
Sim Results			
Network Distance			
Straight Line Distance			
Trip Time			
Passenger waiting times by station (with 2.00 hours of simulation data):			
Station	Mean (s)	% <= 60s	N (groups)
Station 01	9	100	188
Station 02	11	96	192
Station 03	11	97	215
Station 04	14	96	177
Station 05	8	97	185
Station 06	10	98	190
Station 07	21	89	193
Station 08	23	84	193
Station 09	7	100	180
Station 10	15	93	182
Station 11	17	89	187
Station 12	8	100	198
Station 13	9	97	194
Station 14	16	94	199
Station 15	18	90	185
Station 16	8	100	180
Station 17	16	91	177
Station 18	29	79	178
Total	14	94	3393

Fig 4.57 The result table for two-trunk single layer

$$\text{Capacity} = \frac{3393 \text{ veh} \times 30 \text{ pax/veh}}{2 \text{ hr} \times 3 \text{ regions}} = 16965 \text{ pax/hr/region}$$

Comment

Even though the capacity is increased by adding one more trunk to the single layer network, but still lower than that of layered trunk design. Therefore, we can conclude that layered trunk design is more feasible to be implemented in the GRT system design.

4.7 Result Table & Discussion

The mathematical expressions showing the behavior of the GRT system under assumptions can be summarized as follow:

- i. **Duration of in-vehicle interchange (sec)** = $24(N - 1)$

where N = number of coupling vehicles

- ii. **System minimum headway** = 4.32 seconds

- iii. **System maximum capacity (pax/hr)**

$$\min(25000N_t, 8563x_1 + 3335x_2)$$

where N_t = Number of trunks per direction
 $x_1 = \begin{cases} 1 & \text{when } x_2 \geq 2 \\ 0 & \text{otherwise} \end{cases}$
 x_2 = Number of stations per region

- iv. **Total time T travelling through the trunk section (sec)**

$$T = \frac{L_t}{19.44} + 3.908N + 8.826$$

where L_t = Length of the trunk (m)
 N = Number of coupling vehicles - 2

- v. **Regional grid network**

$$\text{Capacity} = 8563x_1 + 3335x_2 \text{ pax/hr}$$

$$\text{Mean trip time } t_r = 142x_1 + 6.1x_2 \text{ sec}$$

$$\text{Fleet size} = 13.3x_1 + 12.65x_2$$

where $x_1 = \begin{cases} 1 & \text{when } x_2 \geq 2 \\ 0 & \text{otherwise} \end{cases}$
 x_2 = Number of stations per region

- vi. **Estimated total trip time (whole system) for a passenger (sec)**

$$\sum_{i=1}^n T_i + \sum_{j=1}^r t_{rj}$$

where n = Number of trunks passed
 r = Number of regional network passed
 T_i = Time (T) of passing trunk i
 T_{rj} = Mean trip time (t_r) of region j

Discussion

Headway

Under the assumptions of vehicle speeds, the minimum headway of 4.32 seconds reveals the provision of high frequency service is possible in GRT. To facilitate the “train of vehicles” operation, maximum speed of the vehicles (80km/h) is designed slightly higher than the normal operating speed (70km/h). The headway thus is *dynamic* – the actual headway can be even shorter under circumstances.

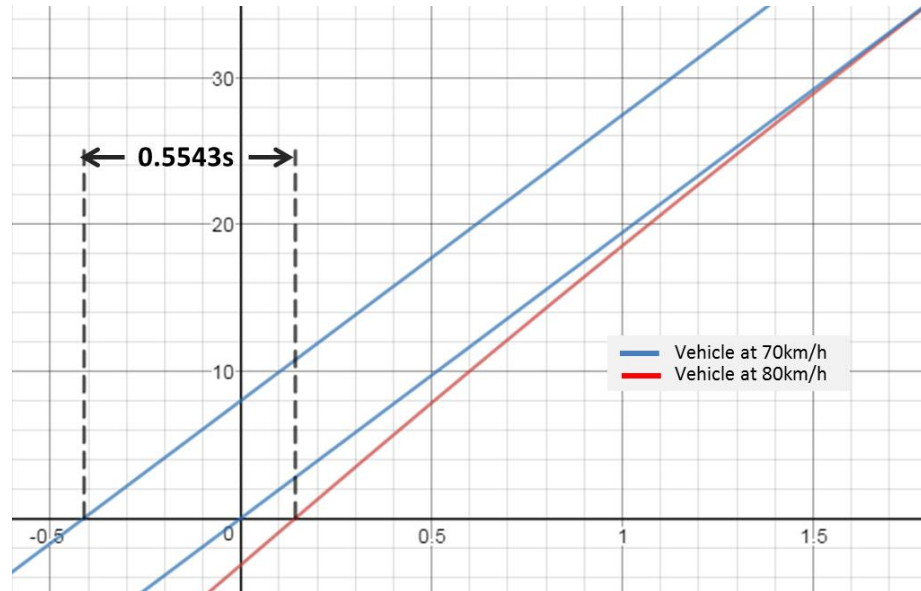


Fig 3.60 (S-t graph) When a vehicle at 80km/h is going to couple another vehicle at 70km/h, the minimum separation is 0.5543 seconds.

On the other hand, the station boarding/alighting time of passengers is about 20 seconds, which is much larger than the headway of 4.32 seconds. Congestion may occur at station if both the passing vehicles and stopping vehicles use the same single track. This has proven the essentiality of the provision of *off-line station* in part 3.5.

Capacity

The system capacity can be determined by two equations – the trunk capacity and the *regional network capacity*. In infrastructure design, the calculation of *the latter* should have the higher priority as travel demand is generated at stations, and stations are in the regional network. The number of trunks is then determined so as to cope with regional demand.

To find out whether the GRT network can handle the travel demand in a specific region or district, trip density (pax/hr/km²) can be calculated which is given by

$$\frac{8563x_1 + 3335x_2}{D^2 \times x_2}$$

where D is the separation between two stations. Number of stations

needed in a region can be deduced by comparing with the statistics of the government transportation and planning department in the country.

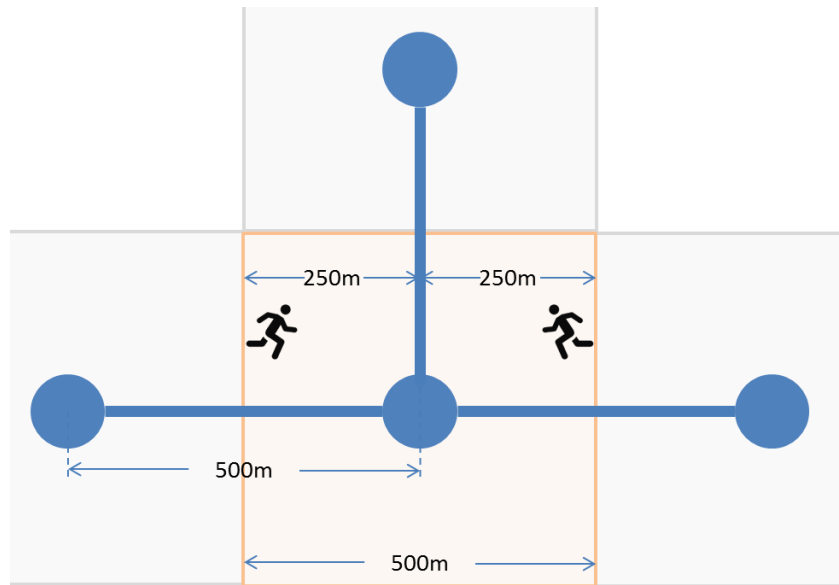


Fig 3.61 Cover area of a station

For instance, the total number of trips using transit generated in Kwun Tong District, Hong Kong in peak hour is roughly 157,071 pax/hr [41]. Thus, this district needs at least 45 GRT stations. Assume 500 m station distance, 45 stations can cover an area of 11.13 km^2 , which is close to the district area of 11.05 km^2 . The calculation shows that GRT system is capable in serving travel demand in this district with only 1 layer of regional network.

If the calculated trip density is far below the requirement, or the district area is far smaller than the calculated network area, multi-layered regional network can be considered for extra capacity.

Travel Time

The total travel time of a passenger trip is the sum of time in the regional networks and time passing the trunk sections. Among the variables in the expressions, the number of stations in the region is significant to the resultant travel time.

Taking the Kwun Tong District case again as example. In the 45-stations region, the regional travel time is about 7 minutes, which is equal to passing a trunk section of 8 km long.

The example shows the GRT favors region-to-region journey. The trunk operation is efficient due to the high speed travel and no junctions, while in regional network the vehicles operate in slower speed and junctions is frequently encountered. This has proven the “branch-and-trunk” structure characteristic, and the importance of separating trunk section from regional network, mentioned in part 4.6.

5. Implementation

Part 5 is a detailed discussion on how a group rapid transit (GRT) system should be implemented as a real world system. This part acts as an implementation guide on system design and specification suggestions, in reference to the results obtained in the previous parts. Available options in different components will be browsed with evaluations.

5.1 Implementation - the Passenger View

Flow of ridership

Summarizing the characteristics and founding mentioned in the previous parts, the flow of taking the GRT can be presented by the following flow diagram:



Fig 5.1 Flow of taking the GRT

1 – The Handheld Gadget

Passenger uses a handheld gadget to register GRT services by entering origin and destination stations. After processing in the server, feedback is given by displaying the train number the passenger needs to board and its arrival time.

Gadgets Description

Token

Like the security token used in commercial banks, a small-sized device can be distributed to passengers by the GRT operator.

Advantages: Self-developed program with encryption, higher security and compatibility to other system components

Disadvantages: Distribution cost, increased personal belongings as users need to bring along their tokens



Smart Phone

Passengers can download freely and install the GRT registration app into their own smart phones.

Advantages: Easy distribution, highly portable

Disadvantages: Security problems, low compatibility due to product varieties in market



Online System

Online registration system can be accessed using personal computer, for passengers with broken token or out-of-battery phone

Advantages: No distribution, higher reliability

Disadvantages: Not portable



Passengers can also register the service through the ticketing machines in stations, if the above methods are all inapplicable.



Fig 5.2 Ticketing machines in station

2 – Station Design

The passengers who registered the GRT service should arrive to the station platform before the displayed train arrival time on their own gadgets. Under such approach, nearly immediate boarding can be possible. The train numbers and their arrival times are also shown on the screen display in the stations.



Fig 5.3 Station screen display

Station design criteria:

- Screen displays should be set at positions that passengers can clearly read the information at any location inside the station.
- Platform should be built at the level of the vehicle floors.
- Automatic platform screen doors should be built to avoid incidents of passengers falling onto and illegal access to the track.
- The platform length should be of enough space for accommodating multiple GRT vehicles. The screen door for each boarding/alighting position is called “gate”.
- Turnstile is not required in a GRT station. The removal can improve passenger flow inside station, and give convenience to passengers handling baggage or with disabilities.



Fig 5.4 Platform screen doors



Fig 5.5 Turnstiles

- Gadget recognition device, which facilitates automated fare collection, should be set at each gate (see 6 - Arrive to Destination).
- GRT stations are unstaffed. Therefore, staff machines should be set for passenger in needed. MTR Whampoa Station is a real example of staff machine implementation.



Fig 5.6 Gadget recognition device



Fig 5.7 Staff machine in MTR Whampoa Station

- Sufficient waiting area with benches should be provided.
- Clear signs and floor lines (braille for the blind) should be drawn to instruct passenger boarding/alighting movements.



Fig 5.8 Platform waiting area



Fig 5.9 Floor signs and lines

- To facilitate passenger movement between ground and station, lifts and escalators should be installed to allow access for all types of passengers and their luggage, equipment, and travel aids.
- Attention must be paid to vertical circulation and the planning and design of street-level entrances and exits.
- Requirements for fire and panic safety should be fulfilled, such as emergency buttons. Sufficient exit lanes are required to evacuate the exiting occupant load in 4 minutes or less.
- As GRT station operates for 24-hours, extensive use of sensors and detector is expected for intelligent indoor energy efficiency. For instance, reduced lighting and air-conditioning requirements can be activated in mid-night hours.



Fig 5.10 Emergency stop button in station



Fig 5.11 Escalator is stopped automatically if no one is using

- Cross-flows should be avoided whenever possible. Passenger flows moving in opposite directions should be separated.
- The number of facilities at any station should be determined from practical issues of travel demand and passenger control.

3 – Boarding the Vehicle

After the vehicle arrived to the station, the train door opens for about 20 seconds (the time depends on number of passengers allocated). Entered the vehicle, the passenger should tap his/her own gadget onto the recognition device to indicate his/her presence. The train door closes automatically only if all the boarding passengers have tapped the device or 20 seconds has passed.

In many railway systems, push buttons are set to open/close the train doors by passengers themselves. London Underground revealed that dwell time at stations would be reduced if the doors were opened by the driver, rather than waiting for passengers to press the button [37]. In Japan, the push buttons aim at reducing door opening, which in turn prevent cold wind in winter blowing into the train compartment.



Fig 5.12 Push buttons in a Japanese train

In GRT operation, the vehicle departs immediately after the door has been closed. Malicious actions may happen, such as pressing the button when the others have not boarded yet, or closing the doors on people, both accidentally and intentionally. These may cause trouble, or even injuries, to other passengers. Therefore, only the boarding passengers should be authorized to close the train door. Besides, the gadget tapping method can recognize a passenger's absence. The route of the vehicle can be re-utilized by deleting the registered trip of that passenger.

In addition, automated platform gap fillers should be installed on the exterior of the vehicle to reduce the risk of stepboard accidents.



Fig 5.13 Platform gap filler

4 - Vehicle Interior Design

If a passenger needs to interchange, information of train number and estimated start time of the interchange will be given on his/her own gadget. The information will also be displayed on the screen inside the vehicle.

Vehicle interior design criteria:



Fig 5.14 Interior of a Crystal Mover C810 train car

- The train number should be clearly displayed for passengers both inside and outside the vehicle.
- Accurate real-time interchange running information should be provided. The information system should have the capability to acquire and display real time delay information. Broadcasting real-time information via the on board audio system is also necessary.
- The size of the seats should be designed to accommodate a majority of the population. Seat legroom should be designed to accommodate a 95th percentile male [38].
- Provision of adequate space for wheelchair users.
- In order to maximize the vehicle capacity at times of heavy passenger demand, the creative use of tip-up seats should be implemented.



Fig 5.15 Train number display



Fig 5.16 Tip-up seats converted into wheelchair parking space

- Interior lighting should automatically adjust in response to ambient light levels.
- Noise level inside the vehicle shall not exceed 75 dB(A) [38]. Plug door design should be used because of airtight, soundproof and reduced aerodynamic drag.
- CCTV should be installed for monitoring interior conditions and improving security.
- Overhead luggage rack is not preferred due to frequent start/stop and turning of GRT vehicles.

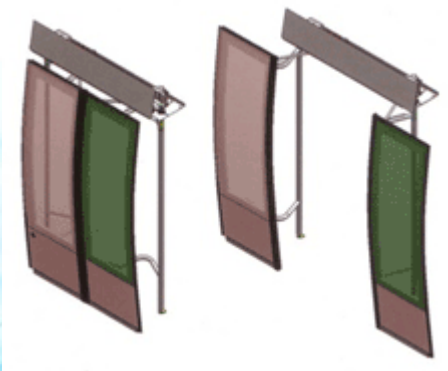


Fig 5.17 Plug door



Fig 5.18 Overhead luggage rack

- Flooring should be chosen to be as slip-resistant as possible. Handrails and overhead hand grips should be installed and able to be used by passengers in all positions of the vehicle.
- Warning signs of door gaps and emergency intercom should be provided with obtrusive coloring.

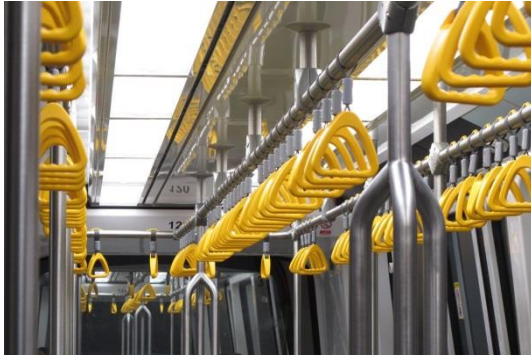


Fig 5.19 Overhead hand grips



Fig 5.20 Emergency intercom

5 – In-vehicle Interchange

After the vehicles have coupled, passengers interchange according to the displayed instructions. The interchange door opens automatically, with obtrusive sounds and light effects to alert passengers.

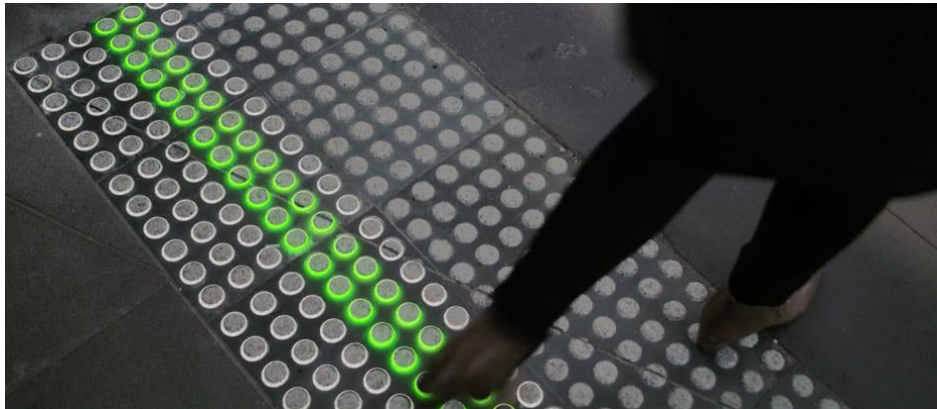


Fig 5.21 Indicator light on the floor

The interchange door should be as wide as possible for (at-least) two-way passenger movement. Doors of sliding type and bi-folding type are preferred due to limited space of vehicle linkage; plug door is inapplicable.



Fig 5.22 Sliding door



Fig 5.23 Bi-folding door

Severe consequence will happen if any passenger or object stays inside the linkage with interchange door closed. Thus, safety should be the most important concern in GRT in-vehicle interchange system. Object sensors with high accuracy should be put into extensive use, and the interchange door closes only if no passenger or other object is detected. Emergency button should be set near the interchange door in case of accident.

6 - Arrive to Destination

When alighted, passengers should tap their own gadgets onto the recognition device installed near the gate screen door. Door closes only if all the alighting passengers have tapped the recognition device, or the 20-second time limit is passed. Fares can be collected automatically through various payment methods, such as bank autopay and credited account under GRT operator.

5.2 Implementation – the Technical View

This part is intended to be used as an aid to preparing a technical specification of GRT system design. It captures the results that have emerged from the previous parts.

The System Tree

The GRT control system structure can be represented by the following hierarchy:

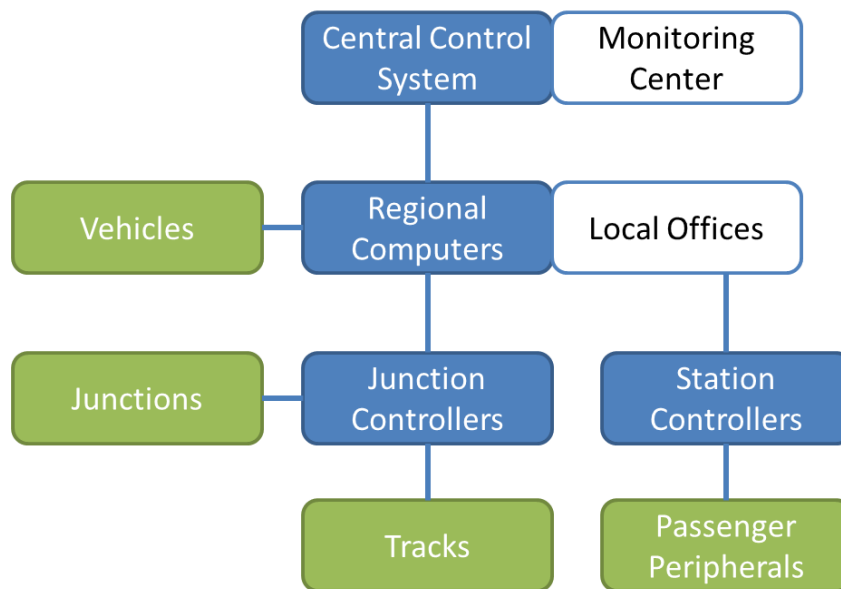


Fig 5.24 Structural diagram of the GRT control system

Central Control System & Monitoring Center

The central control system facilitates the centralized management, algorithm implementation and service quality control of the GRT system. The major duty of the central control system includes mode shifting, trip assignment, and travel pattern analysis:

- *Mode shifting* is the change of operation between demand-responsive service in off-peak and fixed schedule service in peak hours. The shifting involves orderly and efficient transition of algorithm in the whole system thus centralization is necessary.
- *Trip assignment* involves the collection of trip data registered by passengers when demand-responsive mode is in action, then allocating passengers into routes and vehicles. In fixed schedule mode, the system answers the scheduled information instead of trip assignments. The system server is responsible for giving feedback to passengers with train numbers and the alighting times.
- *Travel pattern analysis* is the continuous sampling of trip data, analyzing travel patterns related to trip natures such as home-based work and school trips

in weekdays, and applying the analysis results for a more efficient and realistic trip assignment.

The monitoring center is the central office which monitors the status of underneath sub-system controllers in real-time basis, operated by professional staffs 24 hours a day. Its duties include:

- Ensuring the functionality and maintenance of the central control system and the online server
- Task coordination and communication among local offices
- Crisis management in case of serious incident



Fig 5.25 Central monitoring center

Regional Computers & Local Offices

Each regional computer is responsible in administrating the operation of vehicles within its authorized region. Its major functions are:

- Controlling the movements of vehicles
- Executing the received vehicle routings from the central control system
- Time estimation and fine tuning according to real-time network condition
- Comprehensive vehicle coordination, such as in-vehicle interchange and formation of “train” of vehicles

The local office is responsible for monitoring the movements of vehicles in real-time basis, operated by professional staffs 24 hours a day. Other functions include:

- Ensuring error-free vehicle operation
- Monitoring the working conditions of station peripherals
- Answering enquiries of passengers through the station staff machines
- Station environment adjustments, and evaluations on energy performance of passenger facilities

- The staffs in local office will response to the passengers if the vehicle intercom is triggered.



Fig 5.26 Staff in a local office

Junction Controllers

A junction controller is installed in each junction of the regional network, under the control of the corresponding regional computer. Its responsibility includes:

- Coordinating turning movements of vehicles
- Controlling the rail switches of the upstream and downstream tracks
- By-pass tracks and side tracks of the adjacent stations
- Handover of vehicle control authorizations in cross-regional trunk section

The GRT system should have strong data processing power in serving millions of passengers every day. The hardware should be of high quality. Communication between structures should be of high speed and reliability. Optical fiber communication.

Vehicle Specifications



Fig 5.27 Harbour Island People Mover

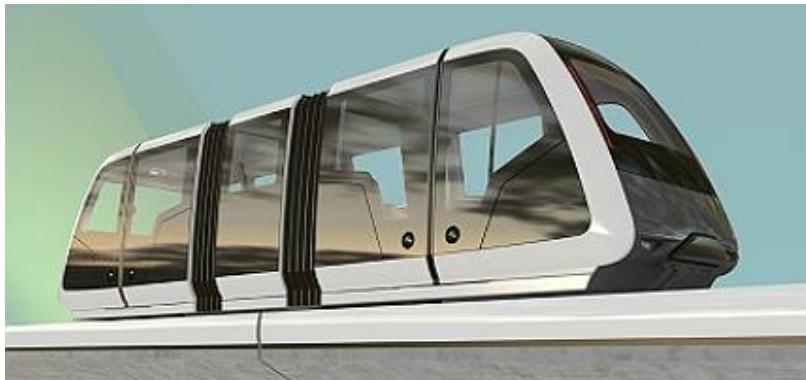


Fig 5.28 Illustration of Vectus GRT vehicle which aims to carry 50 passengers (Retrieved: <http://www.railway-technology.com/features/featurepersonal-rapid-transport-vectus-ferrari-pininfarina/>)

The GRT vehicle is a unit of propulsion with dedicated design meeting the system characteristics. The technical requirements which affect its performance and ridership experience when running on the tracks are:

- Direct current (DC) electrification system should be employed with the following advantages [39]:
 - i. GRT vehicle is expected to have frequent starts and stops. DC motors are better suited for frequent and rapid acceleration than AC motors.
 - ii. DC train equipment is lighter, less costly and more efficient than similar AC equipment.
 - iii. When operating under similar service conditions, DC train consumes less energy than a 1-phase AC train.
 - iv. DC system causes no electrical interference with overhead communication lines.
- Third rail power transmission is recommended outweighing overhead wires. This is especially advantageous in tunneled systems where space above the train is very limited. Moreover, the operation of GRT involves many junction crossings and intercepts, which increase the complexity of overhead cable construction.

- The third rail for DC distribution system is less costly, both initially and in maintenance than the high voltage overhead AC distribution system.

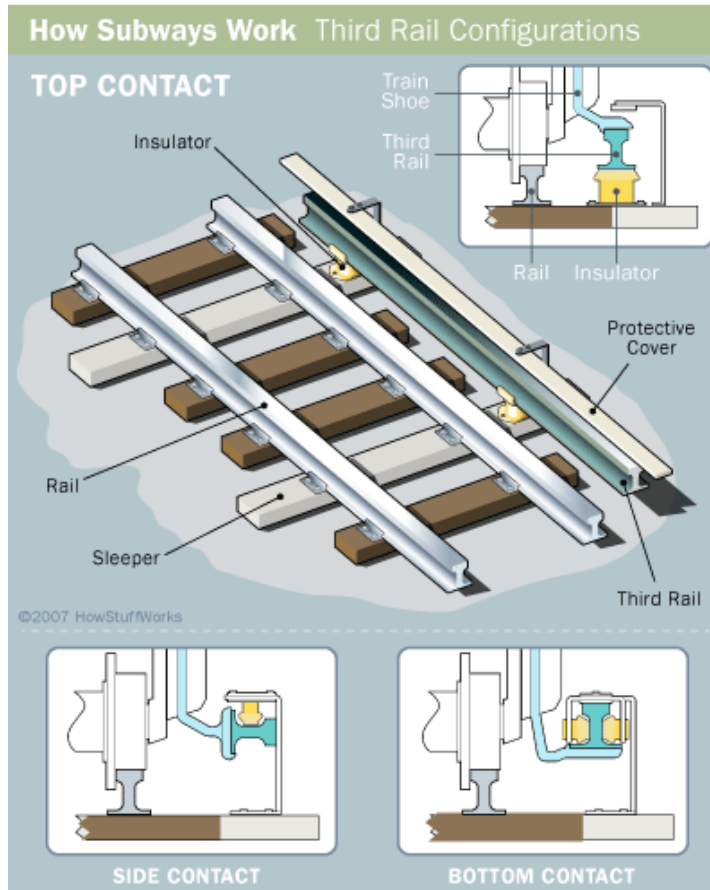


Fig 5.29 A third rail is an additional rail for providing electric power to a railway locomotive or train, placed alongside or between the rails of a railway track

- Systems of a non-critical nature and their supplies shall be kept separate from critical systems so that spurious faults cannot cause the critical system to fail in an unsafe manner.
- Battery can be installed in vehicle acting as back-up supply. Air-conditioning system should be designed to provide a level of emergency ventilation in the event of traction supply failure. Ideally, emergency ventilation should be provided (powered by the vehicle batteries) for 90 minutes [38].
- When vehicle is operating in “degraded mode” as a result of the failure of a key system, the vehicle shall automatically reconfigure, enabling the vehicle to remain in service to the next station. Reporting system should be installed to notify the occurrence of failure to the control system.
- Propulsion systems shall be designed to be capable of rescuing a completely failed vehicle.
- Regenerative braking should be employed for energy utilization.
- Brake blending should give a barely discernible change between dynamic and friction braking in order to give a comfortable ride.

- The speed set system should prevent vehicle speeding in the event of the vehicle descending a gradient.
- The vehicle shall not be able to move, relative to the platform, once it has come to a stop and door interlock has been released. Under this condition, the train shall only be able to move again once door interlock is achieved.
- Vehicle systems shall be designed to operate reliably under all kinds of environmental conditions expected to be experienced. For outdoor system, windscreen wipers should be installed on front windows; splash guards around wheels should be installed to reduce the effects of the build-up of snow.



Fig 5.30 Windscreen wipers



Fig 5.31 Splash guard

- In tunnels the change of pressure can affect a person's health; this limit is 10kPa and is quoted in standards. However as a comfort level a level of 2.5 to 3kPa should be considered [38]. All vehicle doors should be air-tight, and all windows should be designed without opening.
- Vehicle should be fitted with a navigation system. The location as well as time stamp information should then be fed to the control system in real-time basis.
- Forward facing CCTV cameras should be fitted to all vehicles. Night vision capability should be facilitated for underground system. Real-time image should be remotely accessible by the control center.
- Vehicle should support mobile communication without interference. This can be achieved by body shells material selection and signal boosters.
- Vehicles should be designed with intelligent power management systems, with energy use data recorded. On-board systems should only be energized when absolutely necessary. For instance, lighting should be turned off if no passenger in vehicle.
- Air-conditioning system in vehicles should have intelligent temperature adjuster installed. The provision for individuals to adjust the ventilation is also recommended.
- Couplers should be able to function reliably and continuously in difficult environmental conditions (e.g. snow and ice), under mechanical shock and running vibrations.

- Accurate distance measuring sensors should be installed at the front of a vehicle so as to perform “train” of vehicles.



Fig 5.32 Adjustable air conditioning vent



Fig 5.33 Coupler covered by snow

Network Overview

The GRT network should be of right-of-way (ROW) category A - fully controlled ROW without crossings or any legal access by persons or vehicles other than dedicated GRT vehicles. Elevated system or underground system should be considered to isolate road traffic completely.

For network arrangement, a “branch-and-trunk” structure is preferred to provide region-to-region travel service. In part 4.6, simulation has concluded that the arrangement of system without separated trunk section causes performance drag down with conflicts. Grade-separated or layered structure should be implemented, with high-speed trunk section separated from regional network.



Fig 5.34 Grade-separated tracks



Fig 5.35 Layered tunnel

Stations in regional network should be closely distributed. Studies from the University of Sydney revealed the decreasing desire of accessing transit station for walking distance longer than 400 meters [40]. Therefore, the station separation of shorter than 500 to 700 meters should be considered. Under such arrangement, the maximum passenger walking distance can be reduced to 250 to 350 meters.

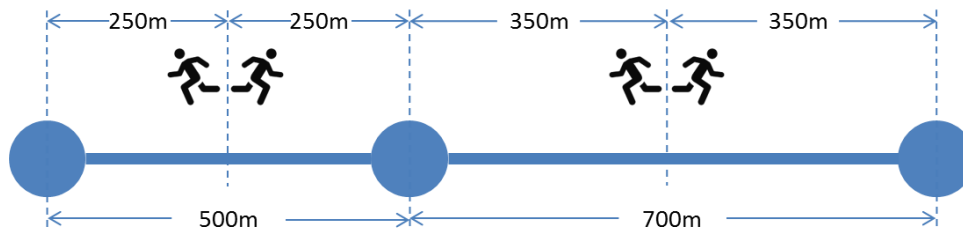


Fig 5.36 Maximum walking distance under various station separations

Uniform regional network should be considered for better route coordination facilitating in-vehicle interchange (part 3.5). Configuration can be of the following:

Grid Network

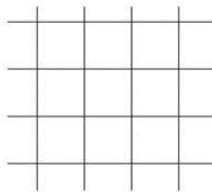
Tracks running at right angles to each other, forming a grid.

Advantages:

- Reduced complexity in calculating travel time if the grid is uniform
- Can go to anywhere with only one turning movement
- Better access in dense city

Disadvantages:

- Double coverage – each point is served by two tracks



Radial-concentric Network

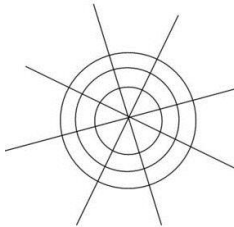
Tracks linking a central point in a region

Advantages:

- Formation of region center
- Can go to anywhere with only one turning movement

Disadvantage:

- Only efficient if region center is so predominant
- Radial lines get further and further apart, longer detour for passengers far away from center
- Non-uniform walking access time



Feeder Network

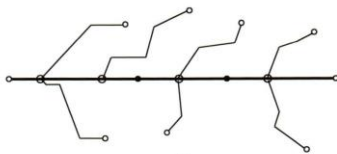
Major corridor with feeder branches

Advantages:

- Higher speed on major corridor
- No double coverage

Disadvantages:

- Inefficient as vehicles need to U-turn at feeder ends
- Longer detour
- Congestion on major corridor



Honeycomb Network

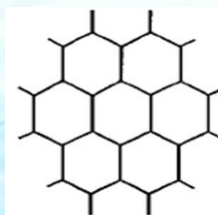
Geometry of honeycombs

Advantages:

- Minimized density of tracks with the same area of coverage

Disadvantages:

- No straight passing movement – all vehicles must turn at junctions
- Lower operating speed



For direction of flow in regional network, two-way system is considerable due to no detour/circuitous route needed. Influence of increased routing combinations and conflicts at junctions can be largely reduced under the use of powerful automated control in GRT system. While, the one way system is still feasible under circumstances due to reduced conflicts and junction passing time, simplified junction algorithm and track design. The actual selection on network parameters should be based on comprehensive transport surveying and strategic transport planning.

Tracks

Tracks in the GRT system should be straight if possible, as curved track lowers operating speed. The curvature and gradient of tracks should following the engineering constraints of vehicle propulsion. Offline stations (by-bass track and side track) should be implemented in all stations to eliminate blockage:

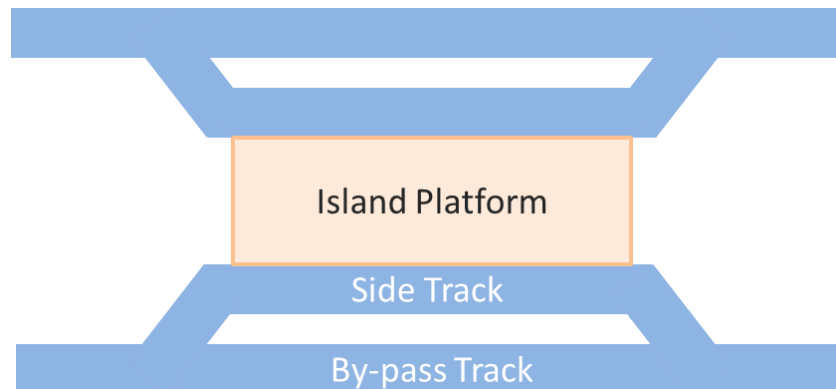


Fig 5.37 Possible off-line station arrangement – island platform

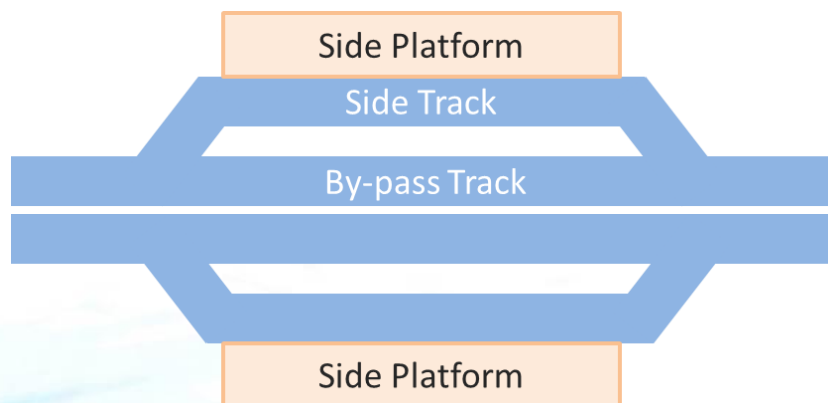


Fig 5.38 Possible off-line station arrangement – side platform

The number of tracks per direction should be determined by the travel demand survey in the planning stage. Capability of different types of tracks for the GRT system:

Steel Rail



Fig 5.39 Steel rail on concrete base

Most of the railway systems in the world are constructed by pair of steel rails. The tremendous historical experiences of its application in the railway industry support the steel rail being one of the cheapest and simplest to construct and maintain. However, the construction cost and visual impact can be huge for elevated system.

Monorail



Fig 5.40 Walt Disney World Monorail



Fig 5.41 Switch of monorail

Monorail has less visual impact to the city view and operates quieter. The monorail can be safer as there is no risk of the carriage derailing. It is easily and less costly to be built elevated, but this advantage is lost if it gets under the ground. The most critical disadvantage is that switches for monorails are big, slow and expensive. This leads to capacity drag-down as the operation of GRT needs frequent switching. Therefore, the monorail is not suitable to be the track of the GRT system.

Suspension Rail



Fig 5.42 Sky Train the suspension railway

A suspension railway is a form of elevated monorail where the vehicle is suspended from a fixed track. Suspended monorail is more costly to construct and, again, the inefficiency of monorail switch makes to not a suitable choice for the GRT.

Guideway



Fig 5.43 Guideway of the Morgantown PRT

Guideway is a type of track that guides the vehicle by edges surrounding the wheels, different from other systems that the vehicle wheels run on the track. The vehicles are often rubber tired, and the guideway normally provides a physical support like a road. For steering, most of the system uses conventional steering – the wheel steers a little until following the appropriate edge (Fig 3.50). This simplifies the guideway, makes junctions less visually obtrusive and reduces the impact of malfunctions. However, such operation needs to be performed in a rather slow speed, as the edge locking mechanism needs to be verified. In addition, it increases the number of small moving parts in each vehicle, while track-switching simplifies the vehicles. Anyhow, the guideway is feasible to be the track of the GRT system.

Maglev



Fig 5.44 Maglev train

Maglev is a transport method that uses magnetic levitation to move vehicles without making contact with the ground. The construction cost of a Maglev system is extremely high, and it is obvious that the GRT system does not need to operate in such a very high speed.



Fig 5.45 Noise barrier



Fig 5.46 Emergency escape

The track should facilitate power distribution and data communications (for example, through the third rail). For outdoor system, the track should also have to ability to resist environmental effects. The guideway in Morgantown Transit has grid of heating pipes embedded to melt snow [22]. Moreover, as GRT stations are often located near residential areas, noise barrier should be constructed the reduce disturbance to residents. Emergency escapes should be facilitated according to the fire regulations in the country.

Junctions

Mechanically, junctions in the GRT system should support multiple turning movements at the same time (Fig 3.48). Railroad switch is preferred as the switching time is a moment's notice; it takes about 3 seconds, which appears capable to the calculated minimum headway of 4.32 seconds in part 4.7. While, the vehicle turning speed on steel rail is higher than that on the guideway. Separation between successive vehicles can thus be much shorter. For higher discharge efficiency, the junction approach can diverge into multiple tracks serving different turning directions. Yet, such implementation needs larger land space.

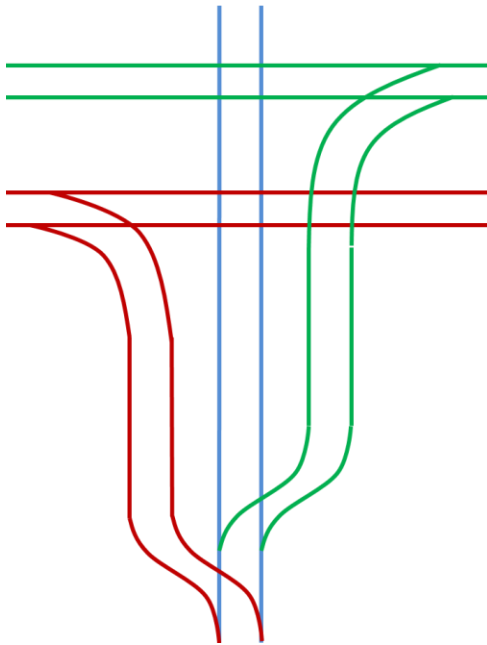


Fig 5.47 Diverged turning approaches

The turning movements at the junction should be neat and efficient; vehicles should not stop at the middle of the junction in any circumstances. The junction priority algorithm should be of high intelligence. Vehicles should be coordinated to pass the junction with least possible delay. Deceleration and stop should be minimized by accurate speed and time estimation.

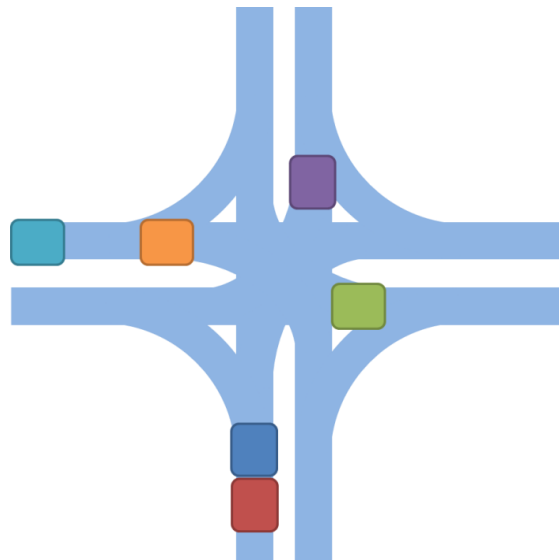


Fig 5.48 Vehicles entering an intelligent junction

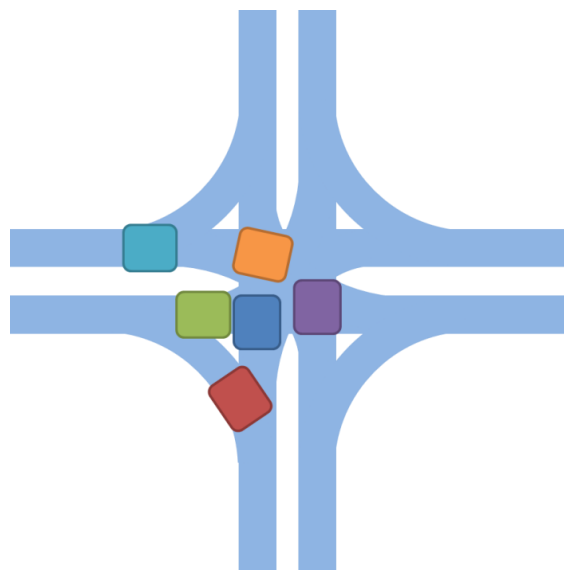


Fig 5.49 Vehicles pass through without deceleration



Fig 5.50 Vehicles were coordinated smartly

5.3 Other Supports

- i. Frequent checking and maintenance for the GRT facilities
 - Vehicles can be designed to facilitate the use of remote condition monitoring equipment to undertake automatic vehicle inspection.
 - On-board condition monitoring systems capable of downloading data to intelligent analytical tools that are able to recommend maintenance interventions
 - At least one depot should be set in each regional network. Empty vehicles can stay at the depot and switch to “stand-by” mode when not in use. This benefits energy efficiency and reduces wear and tear of mechanical parts.
 - When failure is detected, the emergency system inside the vehicle will be activated automatically. The in-vehicle passengers are first discharged to the nearest station. The vehicle then returns to the depot under the supervision of technical staffs in the local offices.



Fig 5.51 Depot in Morgantown Transit

- ii. Reducing the influence of random human behavior through passenger education (such as advertisement and pamphlet)
 - Do not block the train doors
 - Let the passengers alight first
 - Mind the platform gap
 - Do not activate emergency equipment improperly
 - Tap the gadget onto the recognition device when boarding and alighting
 - Do not access the track illegally
 - Do not register a service but not using it

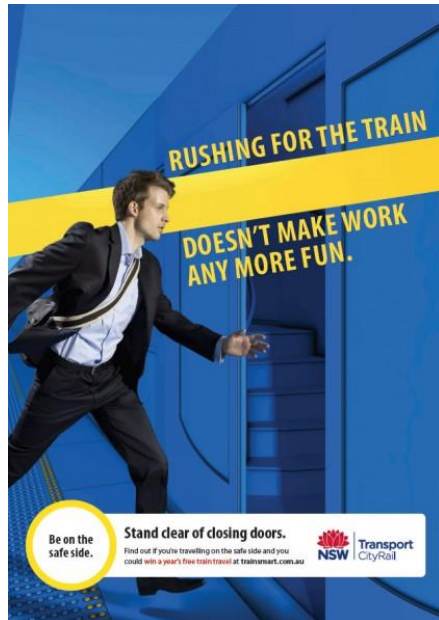


Fig 5.52 Passenger pamphlet

- iii. Setting byelaws for the GRT to improve system and passenger security

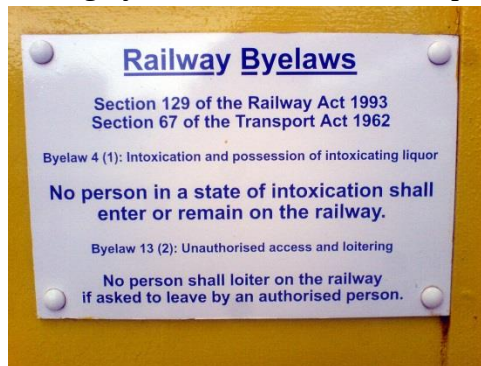


Fig 5.53 Railway byelaws notice

6. Conclusion

To conclude the research, group rapid transit (GRT) is proven to be an afflatus of new world transit system with high intelligence and feasibility. The adoptions of grade-separation and full-automation give the GRT high flexibility and energy efficiency dealing with both peak and off-peak demand. The ridership experience, including access time, safety and capacity, is comparable or superior to the existing transit systems. Indeed, the successful implementation of GRT requires comprehensive cooperation on system design and component suitability. The GRT can be considered as a new transit for a smart city, in where the public transport is completely detached from the private transport. Transit users can enjoy an efficient and punctual ride, ignoring the influence of private car users.

However, in spite of the theoretical performance, the cost of constructing a GRT system is uncertain. The GRT provides high quality service by implementing high-end technology and vertical expansion of space. Besides the system requirements of high intelligent and high processing power, the cost of civil work, both elevated and underground, can be massive. Feasibility study of city-wide deployment in the economic aspect would be an important topic for future researches.

Possible Future Works

- Comprehensive economic studies on GRT implementations
- Development of simulation program in a city-wide scale
- Detailed GRT design standards and guidelines

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