DSB102: Ergonomics and Design of Multi-User Systems

Loughborough Monorail System

Team 5: Mono-Lo

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1. Executive Summary

1.1. The Problem

This project was undertaken as there was found to be issues with the current transport system around Loughborough University and the town. Through user research and observations, it was found that the bus network was slow in travelling long distances, as they spend a large amount of time waiting at intermediate stops and in traffic. This was a particular issue at peak times from 08:30 am to 10:00 am and 4pm to 6pm, and would only get worse with bad weather. The buses also stop operating at night and reduce their timetable in holidays. Access is difficult for the physically disabled, as there is a large step onto the bus. It can be lowered, but this serves to slow the process and highlights their lack of ability. A monorail was needed throughout Loughborough that runs continuously and is accessible and safe for all.

1.2. The Solution

A suspension monorail with an innovative mechanism that allows the vehicle to descend to ground level at stations and ascend again to normal operating height. On arrival at the ground-level station, there is no gap or step between station and vehicle, allowing easy access for all. The systems covers all the desired locations on campus and in town, with 6 stations in 5 locations, based on the findings of a user survey. These are split across 2 tracks - a loop on campus and a straight line into town. This design allows for large distances to be travelled quickly, with no more than one intermediate station per track. There are 2 vehicles on the loop and 1 on the straight track, all of which are controlled automatically, with the option for manual override from the central control room. Continuous operation is ensured with a backup generator and a spare vehicle accessible from either track.

1.3. The Costs

The budget for the project was set at £250,000. The final projected spending was *£200,800*, at nearly £50,000 under budget. The top-level breakdown is shown below:

Total track cost	*£22,800*
Vehicle cost (x8)	*£82,000*
Station cost (x6)	*£39,000*
Control room cost	*£11,800*
Staff cost (x4)	*£40,000*
Extra costs	*£4,800*

Being so far under budget allows any unforeseen circumstances to be accommodated when implementing the system, as often occurs with large projects.

2. Background

Loughborough University has requested that a monorail be built to accommodate the needs of students, staff and visitors with a service that is open to the public of Loughborough. A bus service currently exists that is free for students and staff on campus during working hours, but it only operates during the day, and has a reduced timetable during the holidays. As they use the roads, the buses are subject to traffic and poor weather conditions, which a monorail could avoid.

The monorail is to operate continuously to provide free travel to all, with waiting times at stations no longer than 10 minutes; 24/7 and throughout the year, including holidays.

The monorail must be powered electrically to move the vehicles, a more sustainable option as the grid becomes increasingly powered by renewable energy.

The monorail must operate at a height such that its bottom is a minimum of 5 metres above the ground.

A material that is usable in its many forms for different purposes, Psteel, has been preselected as the material for the entire system, removing material choice from consideration.

The task set is to create all the key aspects of the monorail system - the track, vehicle, the station and the control room, as well as staffing it, while making it safe and easy-to-use for all. This must be accomplished while complying to the relevant standards and legislation and using a budget of less than £250,000.

3. Proposed Solution

The system that has been developed to operate free of charge for Loughborough University students, staff and visitors, available 24/7 both during and outside of term time, providing users an accessible means of transport around campus and into town.

3.1. Stations

The track is split into 2 sections - a loop on campus and a single track in town. There are 6 stations in 5 locations - the loop has stops at engineering, the design school, and the union, and the single track has a station also at the union as well as one in the centre of town and one at the train station. A glass wall is at the front of the station, with sliding doors that open in synchronisation with the doors of the vehicle. The floor of the station has no gap or step to the floor of the vehicle when stopped. There is shelter from the rain, lighting, and benches on the station. The maintenance shed is positioned next to the union stations.

3.2. Vehicles

The design of the vehicles allows for 30 passengers per carriage, including 1 area dedicated for wheelchairs and 3 priority seats. Each vehicle has 2 carriages. The vehicles lower from an operating height of 5 metres to ground level as they approach the station. There are 2 vehicles on the loop, 1 on the straight line and 1 spare.

3.3. Speed

The monorail accelerates and decelerates during normal operation at $1ms^{-1}$, with a top operating speed of $16ms^{-1}$ (57.6km/h). All sections of the track take under 2 minutes to travel across and the maximum waiting time at stations is 1 minute. As a result, one cannot wait longer than 9 minutes, 24 seconds at a station before a vehicle arrives.

3.4. Control room

The control room is located next to the union stations, and contains 2 storeys - the ground floor for a toilet, kitchenette and storage space, and the top floor for the control room. The UI consists of 2 mirror-image desks, one for each track, with 3 control panels and space for documents, as well as a central screen with system information and additional CCTV.

3.5. Staff

4 staff are employed - 2 control room operators, with 8-hour shifts out of phase by 4 hours; and 2 security guards, one for each line.

3.6. Safety

The system has subsystems in place to cope with power outages, lightning, strong winds, rain and floods.

3.7. Cost

The system is well under the allocated budget of £250,000 at £200,800.

4. Research

Fully understanding a problem is a key step in finding potential solutions for it. As such, an initial step after brainstorming was to research the problem from different directions, in order to understand it as well as possible. The focuses were:

- Current bus service
    - Number of users, particularly during peak times (08:45 and 17:00)
    - Number of buses in operation and capacity of each
    - Wait times
- Desired locations for students (as the primary target users)
- Existing monorail designs
- Applicable legislation and standards

4.1. Current bus service

The wait time at stops according to the website (Kinchbus.co.uk, 2016) is 5 minutes, however observation of the stops suggested that it is more commonly up to 10 minutes.
The maximum capacity is about 40 people, with ⅔ of those passengers seated.
With 3-4 buses on campus simultaneously, each bus normally has no more than 35 passengers, even at peak times.
The buses are held up by traffic and bad weather, particularly in town.

4.2. User survey - desired locations

Further primary research was performed in finding where the target population lived, and where they wanted to go to. 49 participants were sampled, using a heterogenous technique (Robson, 2011: 274-275) to include people from as many university schools and living locations as possible. They were each asked where they live and to prioritise the locations to which they wanted to go. The results (Appendix G), weighted by preference order, showed that the locations preferred (in descending order) were the union, the train station, the library, town centre, Holywell gym, Towers/Design school, engineering, EHB, the student village, Loughborough College, and the ‘golden triangle’ in town.

4.3. Existing monorail designs

A number of existing monorails and designs from around the world were examined:

- **Wuppertal suspension monorail** (Wuppertal.de, 2011) - attractive, brings in tourism; moderate speed in town (60km/h); suspension design.
- **Scomi Rail** (Scomi, 2011) - strong consideration of passenger flow and consideration of user anthropometrics; straddle design.
- **Monorail TrensQuébec** (Trensquebec.qc.ca, 2016) - technological innovation for electric vehicles; high speed (250km/h); suspension design.
- **Chongqing monorail** (Hitachi, 2005) - multi-carriage vehicles; straddle design.
- **Mumbai monorail** (Mumbai Metropolitan Region Development Authority, 2016) - multi-carriage vehicles; low operating speed (31km/h); straddle design.

Each had benefits to their design, but there was no clear superior - they were suited to their requirements.

4.4. Applicable legislation and standards

Legislation provides hard limits on what must or must not be done, and so it is imperative to be aware of the applicable sections. It comes from multiple levels of government, however the bodies applicable to this project are the UK and the EU governments.

Standards, also issued at multiple levels, are not inherently mandatory, although may be required by relevant regulations or to meet non-governmental certification. Regardless of necessity, they typically provide best practices and agreed technical minimums that should be adhered to unless there is considerable reason to do otherwise. The relevant bodies here were the International Organization for Standardization (ISO), the British Standards Institute (BSI) and the Rail Safety and Standards Board (RSSB).

The following section discusses the conformity to relevant legislation and standards.

5. Conformity to Legislation and Standards

There are a number of regulations and standards pertaining to the design and operation of railway systems that must be followed, either legally, or as a requirement for certification. Legislation, codes of practice, standards and guidelines have all informed the development of the Loughborough monorail to a degree appropriate to their importance. Where standards have not been found for a particular feature, relevant academic literature has been consulted to find appropriate figures.

The requirements focused on during the development process include the following:

5.1. Vehicles

The Railways and Other Guided Transport Systems (Safety) Regulations (SI 2006/599) (as amended 2015 (SI 2015/1917))

The Rail Vehicle Accessibility (Non-Interoperable Rail System) Regulations (SI 2010/432):

- Power doors
- Seats
- Wheelchair spaces

5.2. Stations

The main standard followed for stations was the code of practice:
Design Standards for Accessible Railway Stations

- Doors
- Lighting
- Floors
- Platforms
- Seating, Waiting areas and Shelters

This included numerous references to PRM TSI (European Commission, 2014) and BS 8300:2009 Design of buildings and their approaches to meet the needs of disabled people.

Network Rail's documents were also consulted regarding station design and weather resilience:

- Guide to station planning and design (Network Rail, n.d.)
- Route Weather Resilience and Climate Change Adaptation Plans (Network Rail, n.d.)

5.3. Control

The control room design follows the guidelines set out in the suite of standards BS EN ISO 11064 (Ergonomic design of control centres:

- BS EN ISO 11064-1:2001 Principles for the design of control centres
- BS EN ISO 11064-2:2001 Principles for the arrangement of control suites
- BS EN ISO 11064-3:2000 Control room layout
- BS EN ISO 11064-4:2004 Layout and dimensions of workstations
- BS EN ISO 11064-5:2008 Displays and controls
- BS EN ISO 11064-6:2005 Environmental requirements for control centres
- BS EN ISO 11064-7:2006 Principles for the evaluation of control centres

Guidelines from the RSSB were used in large part for the control, command and signalling aspects of the project:

- T042 Low cost train control using global positioning system technology
- T087 Defining a standard train control interface for the European Rail Traffic Management System
- T326 Human factors good practice guide to managing alarms and alerts
- T686 Guidance on the use of selective door operation in the GB rail industry
- T892 Data and analysis for a cost-effective GPS-based locator with simple augmentations

The RSSB were also used as a source for information on area-specific cognitive risk factors and safety concerns regarding extreme weather conditions:

- Good Practice Guide on Cognitive and Individual Risk Factors (2008)
- Safety implications of weather, climate and climate change

5.4. Workplace

The suite of workplace regulations known as ‘the six-pack’ have been adhered to. These consist of:

- *Management of Health and Safety at Work Regulations* (SI 1999/3242)
- *Provision and Use of Work Equipment Regulations* (SI 1998/2306)
- *Manual Handling Operations Regulations* (SI 1992/2793)
- *Workplace (Health, Safety and Welfare) Regulations* (SI 1992/3004)
- *Personal Protective Equipment at Work Regulations* (SI 1992/2966)
- *Health and Safety (Display Screen Equipment) Regulations* (SI 1992/2792)

5.5. Environmental

A number of additional environmental standards and regulations were complied with:

- BS EN ISO 7730:2005 Ergonomics of the thermal environment. Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria.
- BS EN 12464-1:2011 Light and lighting. Lighting of work places. Indoor work places.
- BS ISO 8995:2002 Lighting of indoor work places.
- *Control of Noise at Work Regulations* (SI 2005/1643)
- *Control of Vibration at Work Regulations* (SI 2005/1093)

6. Discussion of Solution

A house of quality was created (Appendix B) encompassing each aspect of the system to make the relationships between variables explicit, and to ensure the sections that were prioritised were the most important.

6.1. Vehicle

Each vehicle would consist of 2 identical carriages connected with a flexible link. This has 2 major benefits: shorter carriages allow the track to have curves with a tighter radius, and manufacturing costs are reduced.

6.1.1. Descending & Ascending

A key innovation in the design of this monorail is the ability for the monorail to descend into the station at ground level, rather than require the stations be at the operating height. This is performed by a hydraulic lowering module in between the wheels:power/rail interface and suspended passenger cabin. This makes it easier for all passengers, particularly the physically disabled to board and departing the vehicle.

The idea was found by using TRIZ, a methodology/set of tools for innovative thinking, as described by Rantanen and Domb (2008). The problem is that having high stations is very costly both in terms of construction and the time in ensuring that it complies with various legislation (e.g. lifts, stairs etc), however the track must be at a height so that the vehicles are 5m above the ground during normal operation.

This can be phrased using the TRIZ terminology as a physical/inherent contradiction: The vehicle should be high, but the vehicle should also be low.

This was solved using the separation principles - in particular, ‘separation in time’ - when the vehicle needs to be at the ground-level stations, it lowers down to them, and when the vehicle needs to be high for normal running, it can raise back up.

This was assured to be operable (via a hydraulic scissor-lift system) by the technical advisor.

6.1.2. Internal design

To ensure the safety, comfort and usability of the vehicle cabin for users, anthropometrics were consulted and considered to determine appropriate dimensions for each key component. As the expected passengers are primarily students, staff and Loughborough town residents, the overwhelming majority of users are expected to be adults, or accompanied by one. As such AdultData (Peebles and Norris, 1998) was used as the source of data. The reference provides the mean and standard deviation dimensions of UK adult population, split by sex, for many different dimension. From this, the value of a dimension for a particular dimension is given by the formula (Pheasant and Haslegrave, 2006):

$$X_p = (z_p \times \sigma) + \mu$$

Where:
p = the percentile wanted
X_p = the value at a percentile
z_p = the number of standard deviations from the mean for a percentile ('standard normal deviate' (Pheasant and Steenbekkers in Wilson and Corlett, 2005)) (taken from a standard table (University of Florida, 2013)
σ = standard deviation
μ = mean

Using this, a number of required dimensions were identified and calculated as shown in Table 1 (justification follows).

Table 1: Dimensions and anthropometrics

Associated dimension(s) in carriage	Measurement	Page in Adultdata	Desired percentile	Mean (mm)	SD (mm)	z	Calculated Value (mm)
Door height, rail height	Stature	2	99m	1755.1	69.9	2.33	**1917.967**
Door width, seat width	Shoulder Breadth deltoid	55	99m	496.7	28.7	2.33	**563.571**
Emergency button height	Acromion Height standing	58	99m	1455	63.3	2.33	**1602.489**
Back of seat height	Acromion Height sitting	59	99m	609.5	31.4	2.33	**682.662**
Rail height, Emergency button height	Overhead grip reach	259	1f	1944.3	72.7	-2.33	**1774.909**
Height of seat	Popliteal height sitting	231	5f	398	25.5	-1.64	**356.18**
Seat width	Max hip breadth sitting	86	99f	411.5	41.4	2.33	**507.962**
Seat depth	Buttock to back of knee	216	1f	495.1	36.5	-2.33	**410.055**

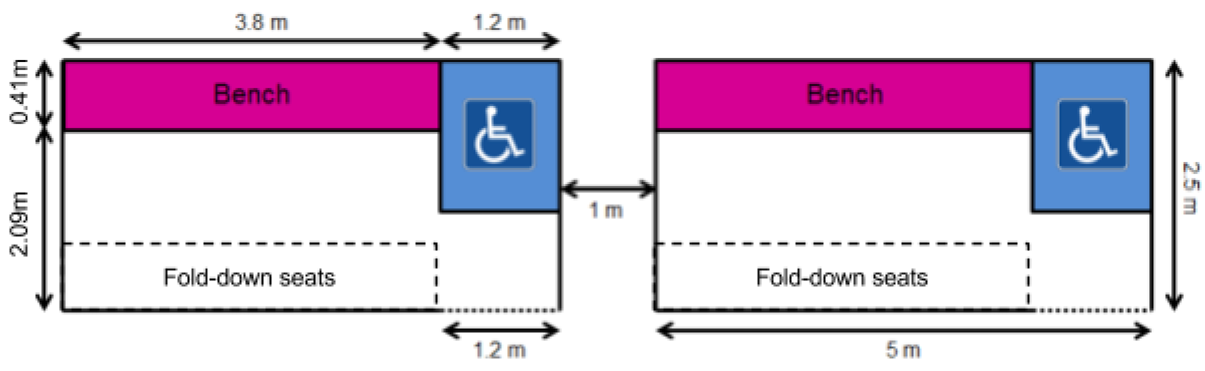
99th and 1st percentiles were used for the dimensions where there was a 1-sided limit (Pheasant and Steenbekkers in Wilson and Corlett, 2005), or when different metrics provided either side of the limit, in order to accommodate as many people as possible. A 5th percentile female was used for sitting popliteal height as it is better for the seat height to be too small than too big, but being too small is still a problem, so it is skewed, but less than other dimensions.

Because the overhead grip reach for a 1st percentile female is less than the stature of a 99th percentile male, the idea for rails had to be changed. Otherwise, tall men would bump their head on it or women with short reach would not be able to reach it. As such, the rails were placed above the tall, with hanging handles reachable by the short, and both avoidable and less injurious if hit by the tall.

The majority of the seating was decided to be in the form of benches along one side of the carriage, allowing more comfort to stretch out when fewer people are aboard. The other side of the carriage houses fold-down seats to allow the option to sit or stand, again depending on the number of people, and also the luggage on board. Luggage space is available under seating and at the end of the carriage. There is ample space for 30 people on each carriage (including both standing and sitting), providing 60 spaces per vehicle - more than enough to cope with high traffic.

Wheelchair dimensions accounted for are specified in *The Rail Vehicle Accessibility (Non-Interoperable Rail System) Regulations 2010* (SI 2010/432) as 1200mm front-to-back by 700mm across (see Appendix H), and so the wheelchair space accommodates this with room to spare. Following the same legislation, 3 seats on the benches (>10%) are labelled as priority seating for the disabled and the wheelchair space has the designated sign. As the height of the seating is required to be 430-500mm high, the seats were made 430mm high.

Figure 1: overhead plan of 2 carriages in a vehicle.



See Appendix E for a mock up of the space required.

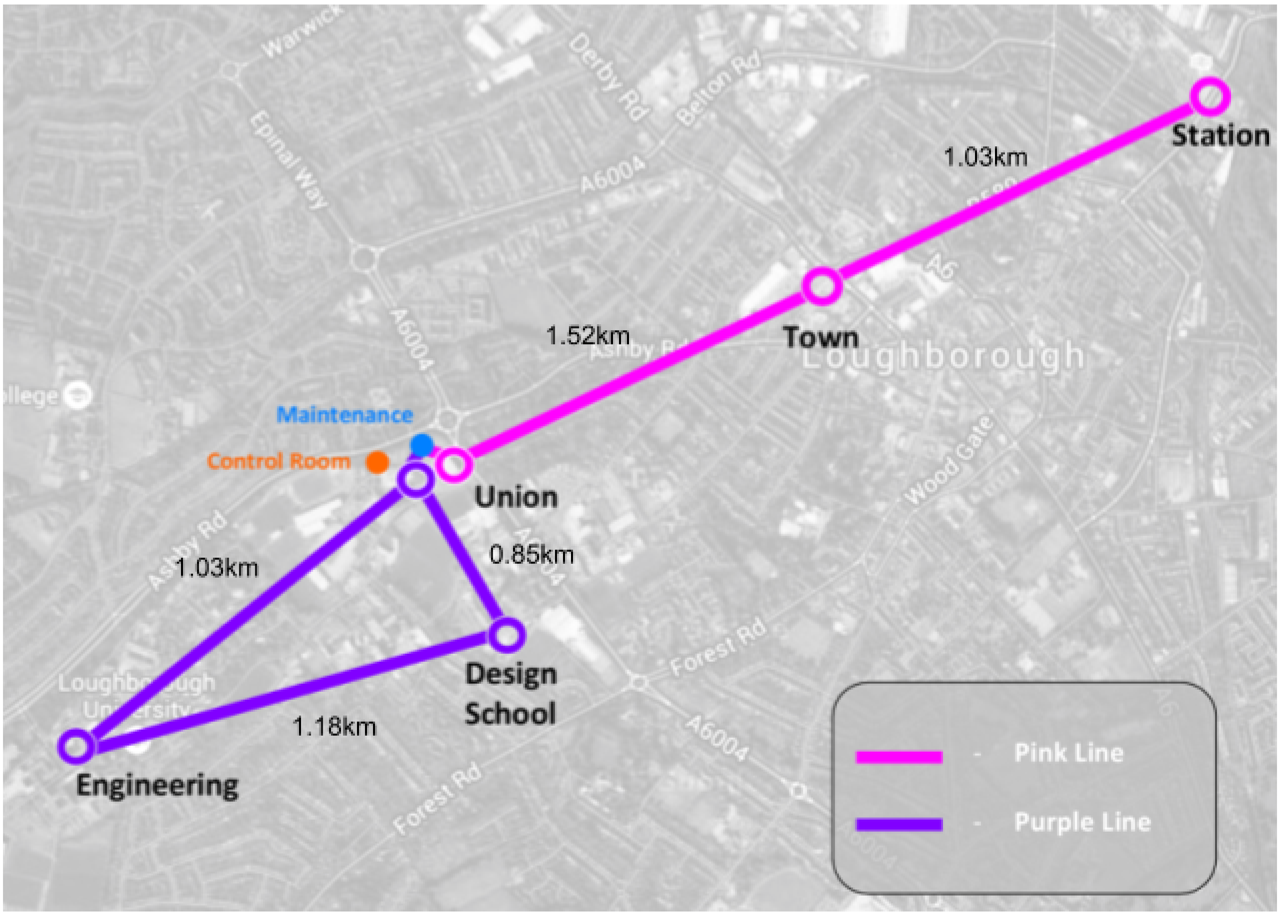
6.2. System Layout

6.2.1. Station locations

Given the continued existence of the bus network, the monorail was thought to be best used as a fast way of travelling extended distances, rather than replacing short walks. As a result, it was decided that there would be only few stations, positioned far apart (over 0.75km). This would allow for greater speeds, and less time waiting at intermediate stations.

Based on the user research, the union, the train station, the library and the town centre all required stations nearby. Positioning the library station further North-West allowed easy access to engineering, Holywell gym, and the student village, and also provided a better location for the station itself. An additional station near the design school allowed quick access to that, Loughborough College and to Towers. This left 5 stations in total.

Figure 2: Map showing length and layout of track, location of stations, maintenance shed and control room



6.2.2. Track

After much consideration, the track was split into 2 sections - a loop going round campus (the purple line), and a straight line from the union, going through the town centre and finishing at the train station (the pink line). These would not be contiguous, but would have stations colocated at the union. There would be 2 vehicles on the purple line that would only go in one direction and a vehicle on the pink line would go back and forth along the same piece of track. This minimised the amount of track needed, being both shorter, and not requiring 2 adjacent tracks, compared to the alternatives. It also meant that stations only had to be on one side of the track, and that the vehicles could be transferred to and from the maintenance shed spurs easily without any tracks crossing, ensuring safety at the points.

The maintenance shed is located near the union, so a small spur from both tracks can reach it, and the control room is also near the union, which, as the centre of the full system, provides the best access to and visibility of all of the track.

6.3. Speed, acceleration and timing

Data from Smith, McGehee and Healey (1978) demonstrate a strong correlation between acceleration of vehicle floorboard or passenger-seat interface and subjective ride ratings. Meta-analysis by Hoberock (1977) regarding acceptable acceleration speeds (based on the comfort of passengers) found that the variability of results from different methods made precise statements difficult, although the author states that:

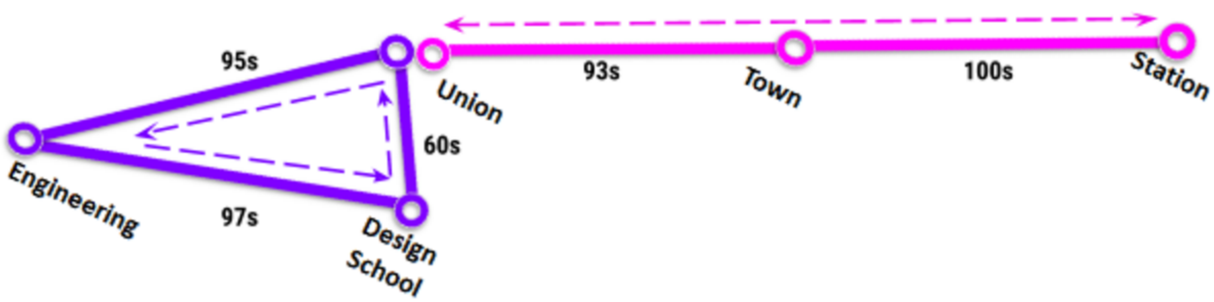
> “The survey did indicate, however, that for public mass transportation, steady non-emergency accelerations in the range 0.11 g to 0.15 g fall in the "acceptable" range for most studies, and could be larger.”

This corresponds to a range of $1.08ms^{-2}$ to $1.47ms^{-2}$ as a conservative estimate of maximum (non-emergency) acceleration.

The system has an operating top speed of $16ms^{-1}$ (57.6km/h). Acceleration is $1ms^{-2}$, below the low end of the (already conservative) maximum. With a maximum wait time at each station of 1 minute, the longest possible wait time occurs on arriving at the union just as the vehicle leaves for the train station - 9 minutes, 24 seconds until it returns.

Figure 3 shows the time taken to traverse each segment of track, taking into account curves with 200m radii on the loop corners. These are needed to allow the vehicles to turn safely. Each section takes less than 2 minutes. The vehicles on the loop travel anticlockwise because speed is more critical on the way to lectures than from them; based on their living location, most students will arrive at the union first on their way into university; and more people want to go to engineering than the design school.

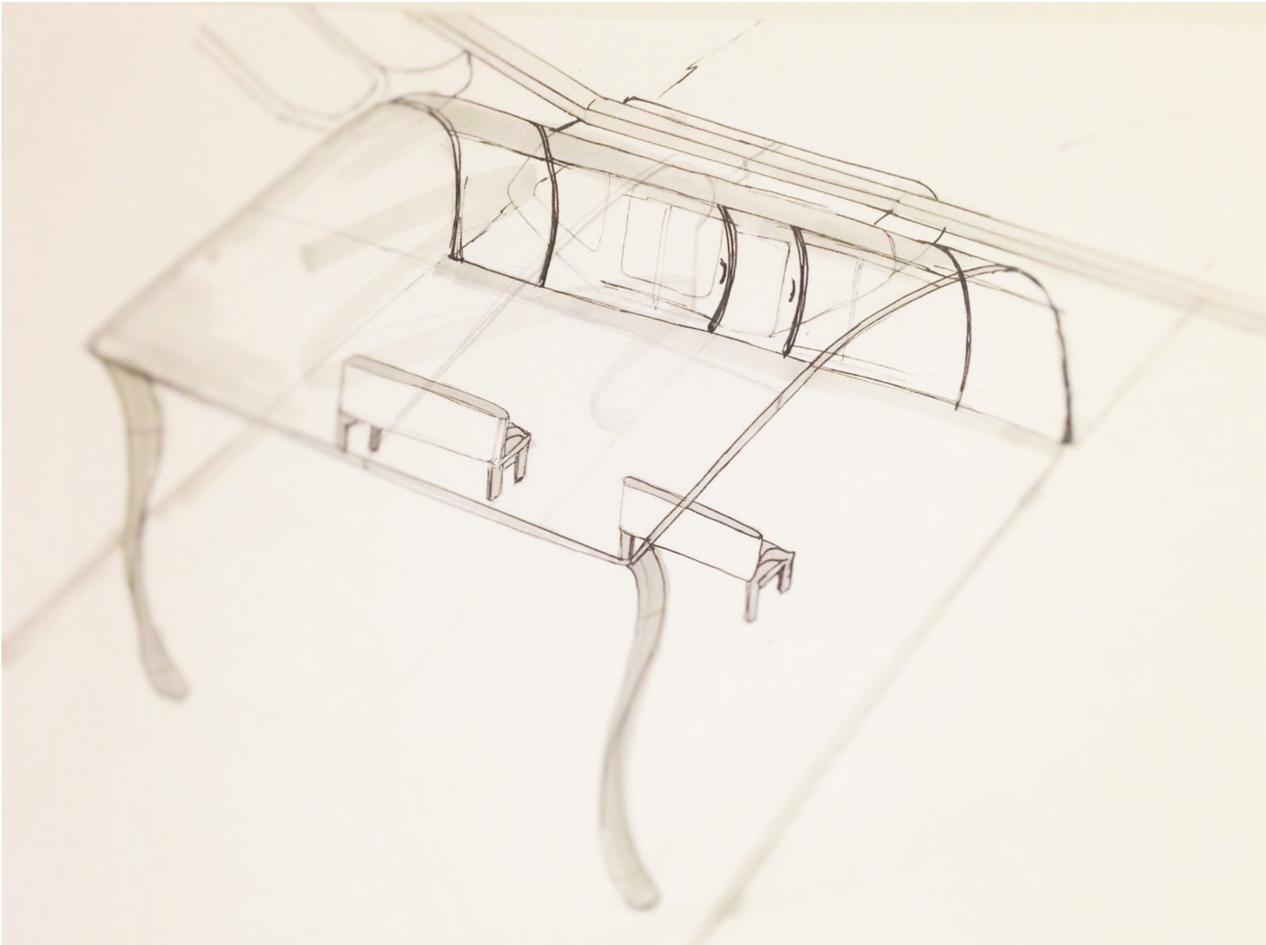
Figure 3: Timing and paths of monorail



6.4. Stations

In order to prevent the possibility of people injuring themselves by stepping off the platform into a moving vehicle, a glass wall was put on the front of the station. This was curved and extended to create an attractive feature on the station, material to which lighting could be attached, and shelter from the rain for waiting passengers (Figure 4). Each station would be 6x3m to allow both vehicle doors to be accessed, and to comply with *Rail Vehicle Accessibility* Regulations.

Figure 4: Concept drawing of station design



The doors would open as the vehicle doors pull up next to them. The floor of the vehicle would come close to flush, with no gap, to the station floor, to allow easy access for wheelchair users and prevent trip hazards for other passengers. A hazard and operability study (HAZOP) was carried out on the opening of the station door to maximise the chances of it working safely and as intended (see Appendix C). As the station is at ground level, it is fully accessible to all.

Following the code of practice from Department for Transport (2015) benches with rounded edges and space for wheelchairs are provided.

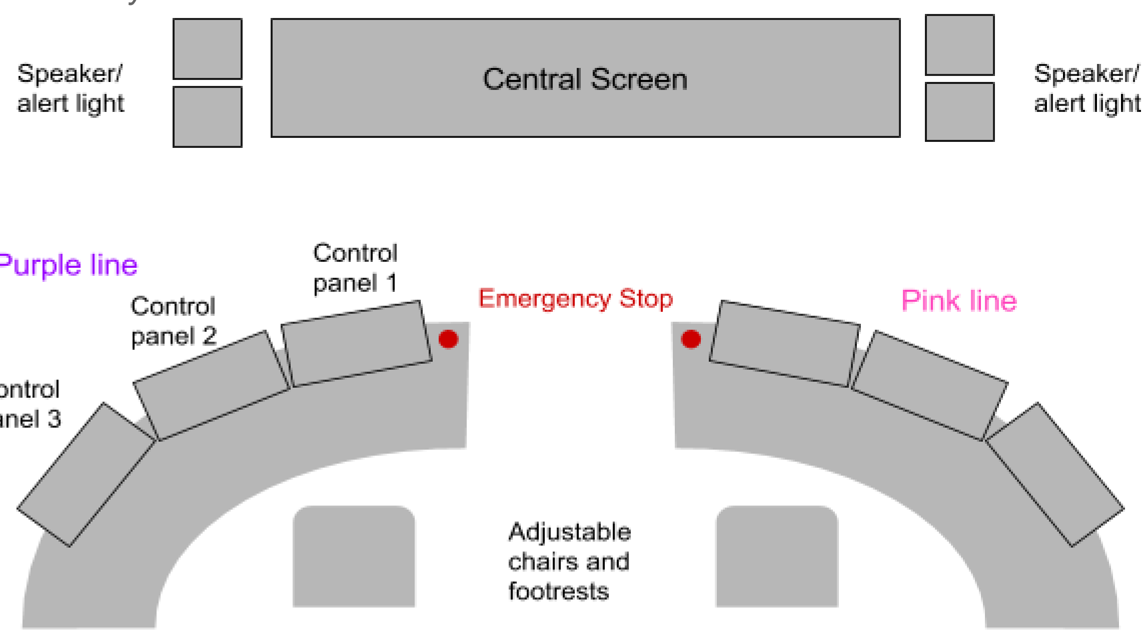
6.5.Control Room

6.5.1. Layout

The control room block consists of 2 floors, each 3x3m. The bottom floor provides a bathroom, a kitchenette, and storage facilities, fulfilling the requirements of The Workplace (Health, Safety and Welfare) Regulations, leaving the top floor for the control room proper.

The control room has 2 desks, one corresponding to each line. 1 member of staff will operate each desk, making 2 positions, each operated for 8-hour shifts. At least 1 person must be in the control room at all time. The shifts of the 2 positions are out of phase by 4 hours, ensuring that any pertinent information regarding running issues can be easily transferred. The desks are positioned in the middle of the room, with control panels on them leaving sufficient space for documents. The primary control panel is straight ahead of the operator, with less important panels positioned at an angle. There is no divider between operators, so that they can discuss relevant information and provide a second opinion without leaving sight of their own panel. There is a large screen at the front with shared information on the track, the system in general, CCTV, and the weather.

Figure 5: Layout of control room



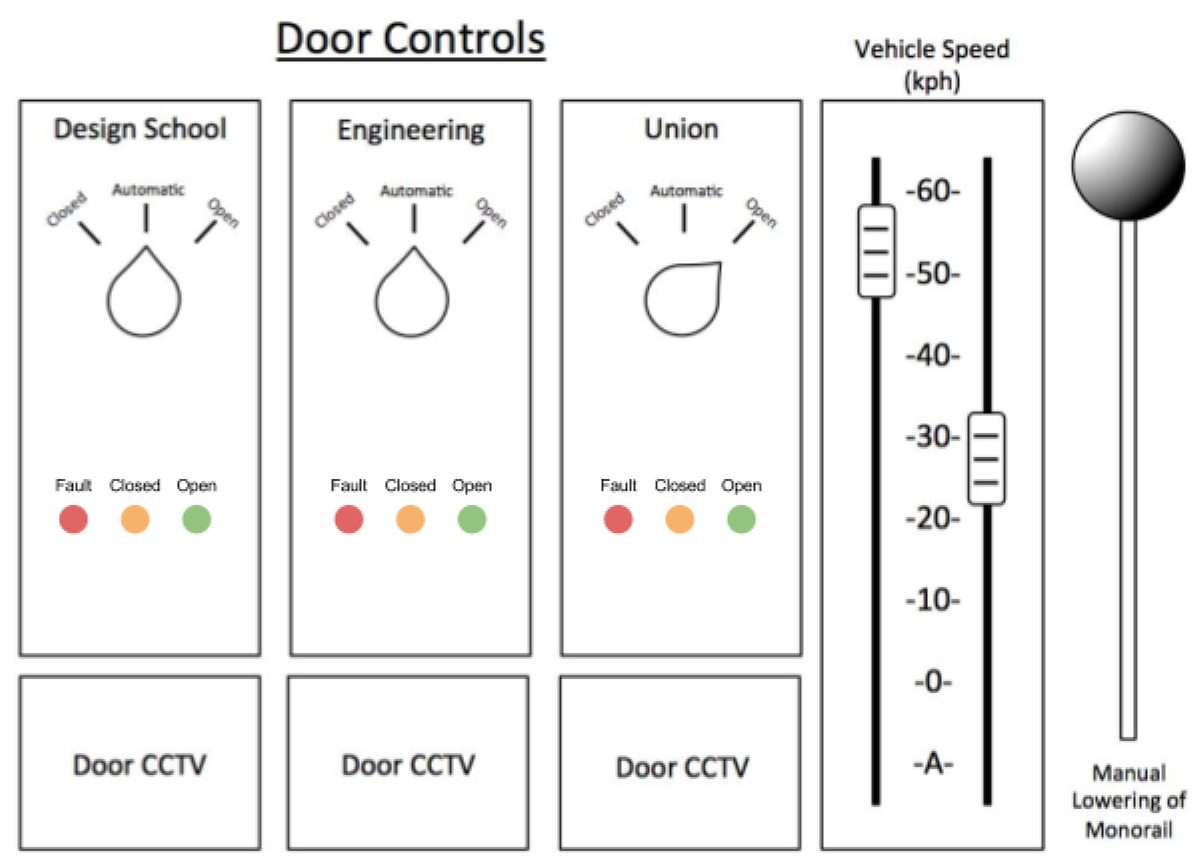
6.5.2. Control System

The system was decided to be controlled automatically under normal operating conditions, partly via GPS, using the RSSB standards as guidance. The vehicles lower as they approach the station, and the doors on the vehicle and the station open simultaneously. To ensure there are no crashes between vehicles on the loop, a policy was implemented that requires there to always be a station between them. If a vehicle arrives at a station and the other is on the next section of track, the former will wait at the station until the latter has left the next station. There is manual override for all functions in the control room, and an emergency stop both in the control room and in the cabins. Manual lowering of the vehicles to ground height is also possible, but requires the area below to be checked and kept clear to prevent harm from coming to anything.

6.5.3. UI

The controls for the system were created to be easily distinguishable both visually and by touch (Sanders and McCormick, 1993), using inputs that are both analogous to the actions they represent and done with sufficient ease relative to their severity. For instance, manual override to lower a vehicle involves a key-locked large lever. Station doors are controlled with rotary detent-positioned dials (Hunt, 1953), with the ‘automatic’ option vertical, allowing inspection that it is instructed as intended at a glance. The information needed is grouped by associated function, as door status and the CCTV covering the door (depending on the information level needed) are on the same panel as the door controls. Sliders behind a cover and requiring inward pressure before sliding (preventing accidental bumps) adjust the speed of each vehicle relative to the intended speed to make sure they are on schedule and in no risk of joining the same section of track. (See Figure 6)

Figure 6: Closeup of one common-usage control panel (not to scale)

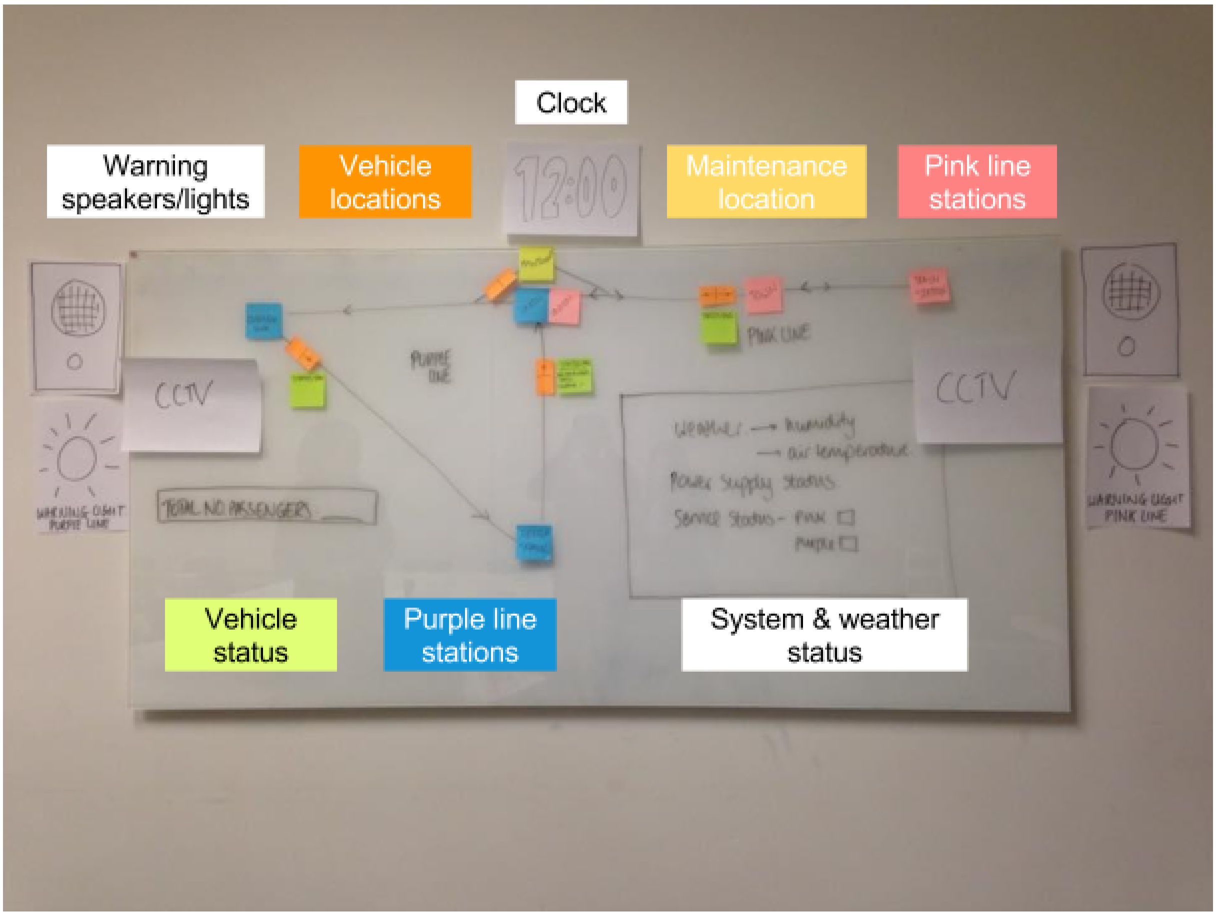


System feedback comes from the large screen at the front, including vehicle status, position and speed, passenger numbers, CCTV, weather status, along with flashing displays and audio speakers for alarms/alerts if something is not as intended. (See Figure 7).

The metric for each status indicator is measured with as little proxy as possible, to prevent the misunderstandings of the type involved in the 3-mile island disaster (Nrc.gov, 2014).

A mock-up of the control room was created, including control desks and the central screen (Appendix E, Figure 7) and a number of scenarios were acted out to test the layout of the controls.

Figure 7: Mock-up of shared front screen layout (coloured labels match post-its)



6.6. Internal environment

Environmental factors were considered for both the vehicle and the control room to optimise comfort and performance:

- Thermal environment - BS EN ISO 7730 provides formula using a number of environmental parameters to calculate how comfortable people will be. It also states that with one setting, a minimum of 5% will always be dissatisfied. As such, adaptive opportunities (Parsons, 2014) have been provided in the form of small openable windows
- Lighting - Complying with BS EN 12464-1:2011 and BS ISO 8995:2002, lighting will come predominantly from natural light through windows, positioned to avoid glare. Lighting will have flicker no lower than 30kHz and provide illuminances of control room working surfaces of 500 lux and the vehicle cabin at 200 lux. Additional task lamps will be available at the control room desks.
- Noise and vibration - vibration will be dampened and the resonant frequency made different from the wind, to comply with *The Control of Noise at Work Regulations* (SI 2005/1643) *Control of Vibration at Work Regulations* (SI 2005/1093)

6.7. Safety, security and continuous operation

In case of power failure, there is a backup generator capable of transporting the vehicles to the next station to let passengers off there.

Many hazardous weather conditions have been accounted for:

- The support columns contain lightning rods, and the compartment itself has a conductive layer that acts as a Faraday cage.
- The natural frequency of the system is to be kept very different from the range of frequencies produced by strong winds, along with vibration dampening will mitigate any effects of resonance.
- The control room is a storey above ground level, so is still operable during floods.
- Cabling is kept insulated from rainwater.

There are 2 security staff at all times, one for each line (again with 8-hour shifts), to protect the physical and mental security of passengers.

A spare vehicle is kept in the maintenance shed, so that if one fails, it can be immediately replaced (on either track) while the broken one is repaired.

7. Discussion of Discarded Ideas

A number of discarded ideas included different layouts for the track:

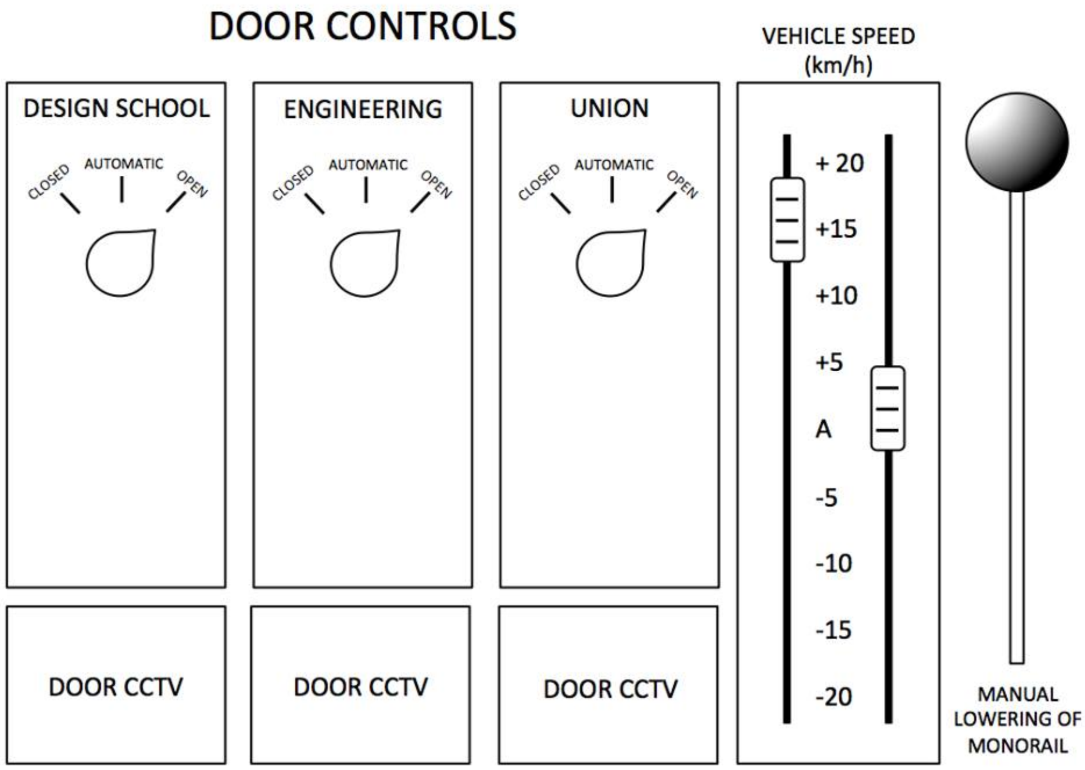
- Any track where vehicles went in opposite directions at any time was ruled out as it creates too great a risk of crashes.
- A 2-sided loop that went to all the stations mentioned above - this would involve more track, involve longer journey times, require 2-sided stations, and present hazards in getting vehicles to and from the maintenance shed.
- A 2-sided straight line would again require 2-sided stations, and would also need large loops at either end for the vehicles to turn, wasting time, or only one vehicle could be on each track, which would make it confusing picking a station side, as it would depend on the time and where the vehicle was coming from. This would necessitate long waits at the platform.

There was consideration of splitting the desks by function rather than by rail, or having the lines control differently, however this would create confusion if the employee practiced with one desk has to operate the other, unfamiliar one, during an emergency where the other employee is out of the room.

Having the monorail operate as a straddle design would prevent descent into the stations (without exorbitant costs and engineering difficulties), and therefore require stations be higher, with lifts, ramps and stairs. This would cost more, possibly removing money from other aspects of the system, forcing compromises that reduce the safety, performance or comfort of the system.

A previous iteration of the main control panel (Figure 8) had the vehicle speed adjustment relative to the automatic speed. This allowed for easy relative adjustments but was found to be confusing during the trial - it was difficult to gauge what speed the monorail would be set at. It also had too small a range of speeds - the vehicle could not be gradually brought to a stop or to full speed. The text was also changed from uppercase to title case, as this is easier to read (Sanders and McCormick, 1993: 108).

Figure 8: Unused control panel iteration



8. Cost

Monorail Cost	Total Budget = £250,000				
Track	No. of track sections	112	cost:	11200	
	No. of supporting pillars	112	cost:	11200	
	No. of points sets	4	cost:	800	
Total track cost					23200
Each vehicle cost	Basic cost (2m x 3m)		cost:	1000	
	Extra sq. metres of floor space	6.5	cost:	3250	
	No. passengers for fitments	30	cost:	6000	
	No. of sq. metres for first stacked floor	0	cost:	0	
	No of sq. metres for second stacked floor	0	cost:	0	
	Total cost for a single vehicle		cost:	10250	
All vehicles cost	Total number of vehicles	8			82000
Each station cost	Basic cost (3m x 5m)		cost:	5000	
	Extra sq. metres of floor space	3	cost:	1500	
	Number of escalators/stairways/lifts/ramps for station	0	cost:	0	
	Total cost per station		cost:	6500	
All stations cost	Total number of stations	6			39000
Control room	Basic cost of room (9 sq. m)		cost:	10000	
	Extra sq. metres of floor space	9	cost:	1800	
	Total cost of each control room		cost:	11800	
All control rooms cost	Number of control rooms	1			11800
Staff provision per person	Number of Staff	4	cost:	40000	40000
Extra costs	Benches on station				4,800
Total Cost					200,800

Word Count: 4950

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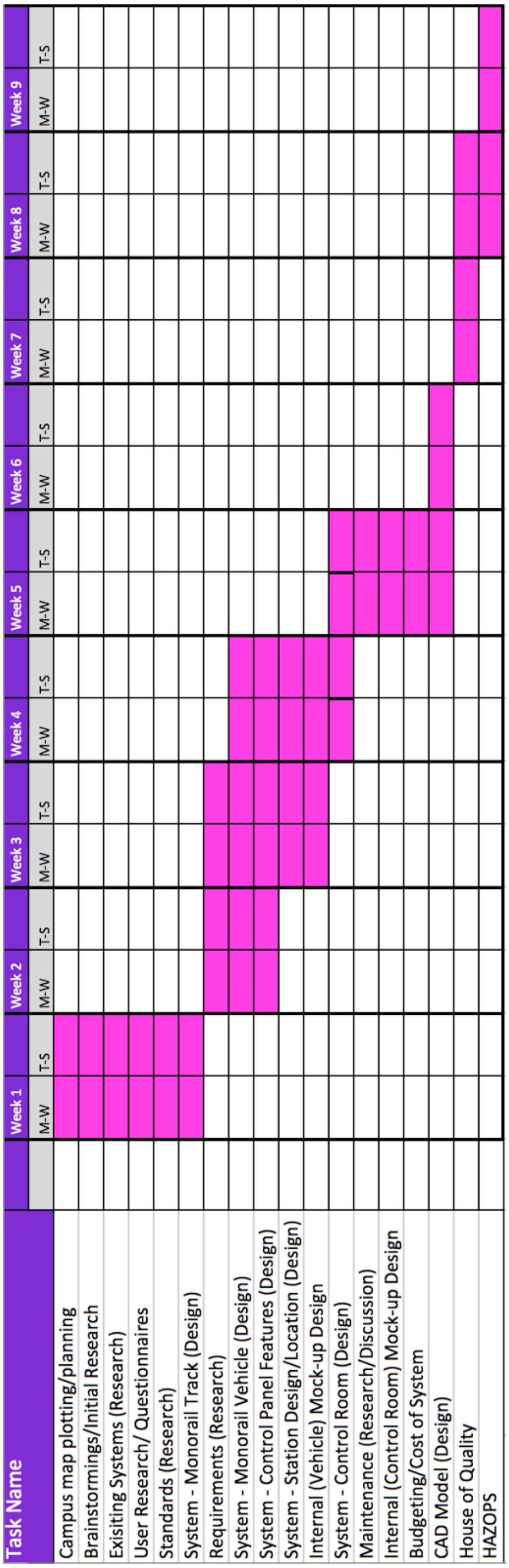
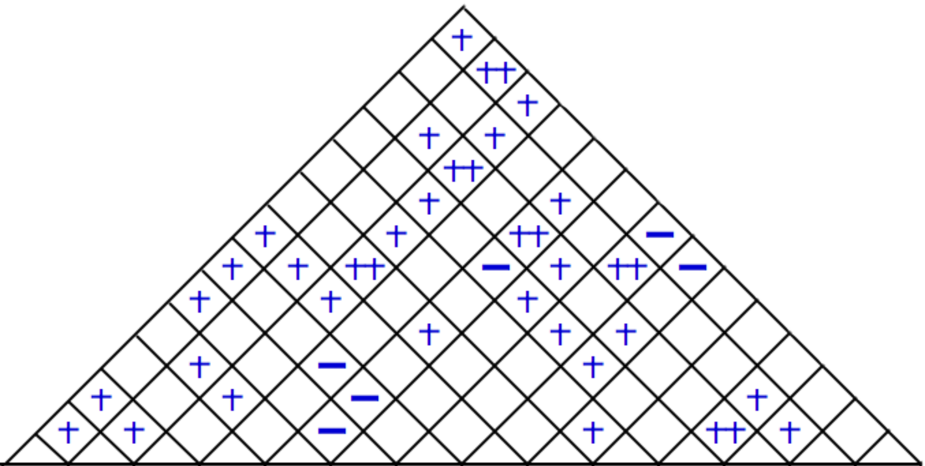
Appendix A: Gantt chart



Appendix B: House of Quality/Design Matrix

Legend		
Θ	Strong Relationship	9
O	Moderate Relationship	3
▲	Weak Relationship	1
++	Strong Positive Correlation	
+	Positive Correlation	
−	Negative Correlation	
▼	Strong Negative Correlation	
▼	Objective Is To Minimize	
▲	Objective Is To Maximize	
x	Objective Is To Hit Target	



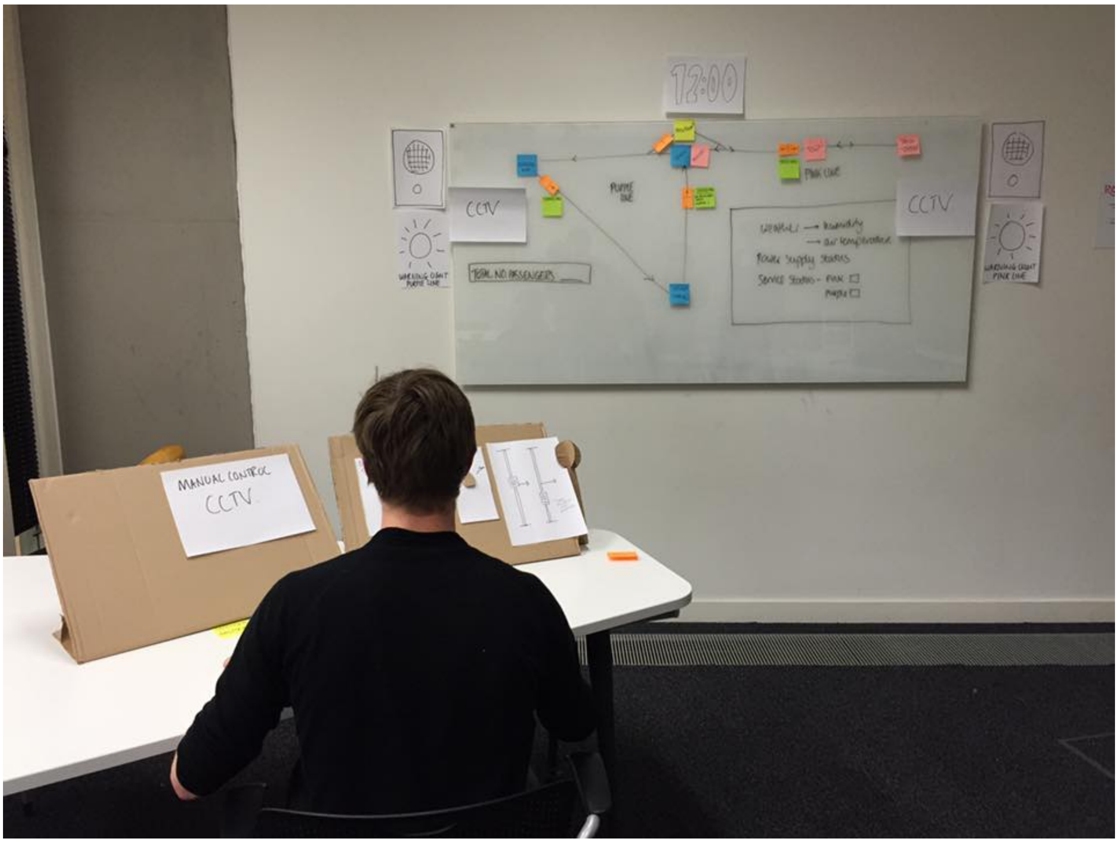
Row #	Max Relationship Value in Row	Relative Weight	Weight / Importance	Column # / Quality Characteristics (a.k.a. "Functional Requirements" or "Hows") / Demanded Quality (a.k.a. "Customer Requirements" or "Whats")	1 Cost	2 Maintenance without stopping service	3 Adequate emergency procedures	4 Stations in key locations	5 Procedure and structures for adverse weather conditions	6 Adequate ventilation system - heating and air conditioning	7 Have base of vehicle a minimum of 5m above the ground	8 Automated system for standard operation	9 Manual override option in case of emergency	10 All required controls in a single control room	11 Access to sufficient power supply - electrics	12 Back up generator in case of power failure	13 Sufficiently strong hydraulic system	14 Replacement vehicle
				Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x)	▼	x	▲	▲	▲	▲	x	x	x	▲	▲	▲	▲	x
1	9	20.4	10.0	Safe travel within the vehicles and on the platform	O	▲	Θ		Θ	Θ		Θ	Θ	O	O	Θ	Θ	Θ
2	3	10.2	5.0	Short travel time	▲		O	O			▲	▲	O	▲	O	▲	O	▲
3	3	6.1	3.0	To stay dry whilst waiting at station in the rain	▲				O									
4	9	10.2	5.0	Easy to get on and off vehicle	O		▲		O		O	Θ	Θ	▲	O	▲	Θ	
5	3	2.0	1.0	Easy to bring luggage - inclusion of luggage storage	▲			▲									O	
6	9	4.1	2.0	Comfortable physical environment - temperature etc.	▲				O	Θ		O	O	▲	▲	▲		
7	9	12.2	6.0	Short waiting time (<10 minutes)	Θ	▲	▲	O	▲			O	Θ	O	O	▲	▲	O
8	9	8.2	4.0	Travel at any time of the day	O	Θ			▲	▲		Θ	▲	▲	O	▲		O
9	9	12.2	6.0	Wheelchair and pushchair access	▲		O	O			O	▲	▲		▲	O	Θ	
10	9	14.3	7.0	To get to key locations with minimal distance between start and finish	Θ	▲	▲	Θ							▲	▲		
				Target or Limit Value	250,000			Maximising user questionnaires satisfied								capable of moving vehicles to next stations	lowering and raising vehicles in and out of stations	Replace other vehicles during maintenance
				Difficulty (0=Easy to Accomplish, 10=Extremely Difficult)	5	7	7	6	6	4	5	4	4	6	6	5	7	8
				Max Relationship Value in Column	9	9	9	9	9	9	3	9	9	3	3	9	9	9
				Weight / Importance	389.8	120.4	287.8	234.7	265.3	228.6	77.6	420.4	449.0	130.6	214.3	279.6	434.7	255.1
				Relative Weight	10.3	3.2	7.6	6.2	7.0	6.0	2.0	11.1	11.9	3.4	5.7	7.4	11.5	6.7

Appendix C: HAZOPS table

Action	Guide Word	Cause	Effect	Symptoms	System Defences	Human Recovery	To Do
Safety doors at stations open	**More**	Overpowered	Opens too fast - damage to mechanism		- Surge protector	Shut off power to door, open manually	Door power shutoff on station (fine for inappropriate use) to allow manual operation
					- High quality parts		
					- Direct physical sensor for 'open' in automatic system		
	Less	Underpowered	Opens too slowly - impedes flow of passengers	Too few people get on	- High quality parts	Use other door	
				System runs slowly	- Backup generator (eg for brownout)	Open door manually	
	None	No Power Locally	Door does not open	Other electrics functioning	- High quality parts	Open door manually in/out	Provide means and instructions for manual operation
					- Power needed to keep door locked (auto unlocks)		Ensure supplier can deliver
		No Power Globally	Door does not open	Other electrics not	- Backup generator	Open door manually out	Ensure supplier can deliver
		Object blocking doors	Door does not open	Door attempts and fails to open	- Sealed gap between sliding door and wall	Use other door	
						Call maintenance/remove blockage yourself	
	As well as	Leaning on door	Fall through door when opened		- Provide seating		
					- Notification of door opening (light & sound)		
					- Ease in to open motion		
	Partly	Door opens halfway	Passengers requiring larger door space	Impedence of passenger flow	- High quality parts	Open manually	
			(eg wheelchairs, pushchairs, luggage,		- Manual override		
	Early	Automation issues or poor manual control	Door opens before vehicle arrives	Bug in automation software	- Well designed software (eg test-driven development)	Not go through the open door	Hire competent programmers
				Operator error	- Control room design considers human factors	Operators take manual control of door	Ensure control room design minimises likelihood of this
	Late	Automation issues or poor manual control	Door opens just before vehicle leaves	Bug in automation software	- Well designed software (eg test-driven development)	Passengers operate manually earlier/wait	
				Operator error	- Control room design considers human factors	Operators take manual control of door	Ensure control room design minimises likelihood of this
					- Deadlock to stop vehicle moving if door is open		

Appendix D: CAD models

Appendix E: Testing mock-ups



Appendix G: Students’ preferred locations

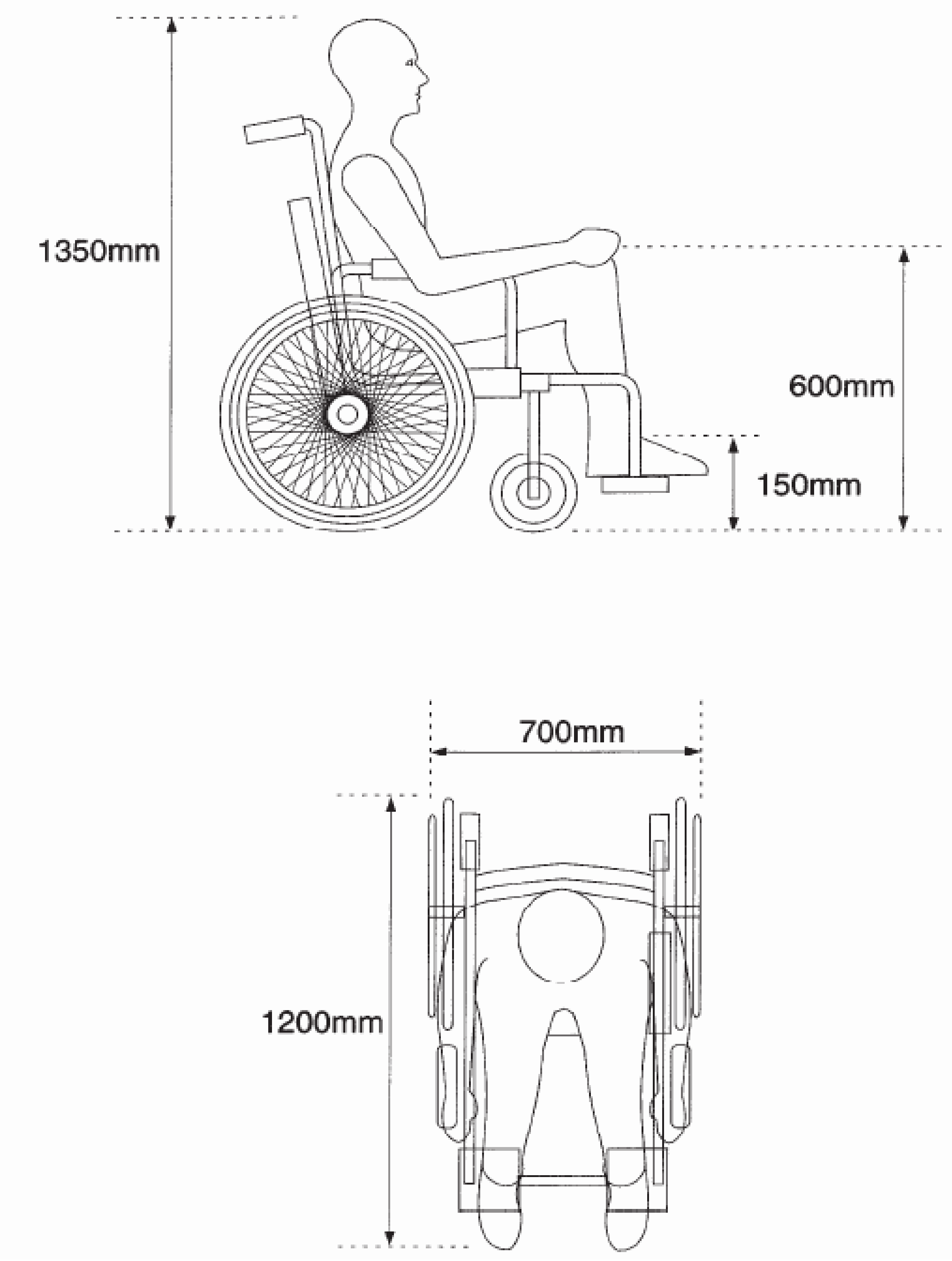
	Preference 1	Preference 2	Preference 3	Preference 4	Preference 5	Preference 6	Preference 7	Preference 8	Preference 9	Preference 10
Train Station:	15	8	9	3	4	2	0	0	0	0
Union	14	11	11	8	0	0	0	0	0	0
Library	8	7	4	2	4	1	2	0	0	0
Town Centre	5	12	3	1	4	1	1	1	2	0
Holywell Gym	3	1	6	7	2	3	1	0	0	0
Towers/Design	2	3	1	4	3	0	0	1	0	0
Engineering	1	4	4	0	4	0	2	0	2	0
EHB	0	3	5	1	2	2	1	0	0	0
Student Village	0	0	0	3	2	1	0	2	0	0
College	0	0	0	0	0	0	0	0	0	4
Others	Home(Triangle)									
Extras	1									
SubTotal	48	49	43	29	25	10	7	4	4	4
Total	49	49	43	29	25	10	7	4	4	4

Appendix H: Wheelchair dimensions

Source: *The Rail Vehicle Accessibility (Non-Interoperable Rail System) Regulations 2010* (SI 2010/432)

Diagram A (reference wheelchair)

(Regulation 2(1))



Lessons Learned and Comments

The value of starting in earnest immediately for projects of this scope became quickly apparent. We did, and saw other groups who did not, struggle to finish. We had ample time to reconsider decisions as a result, which meant a higher quality end product. Related to this, it is well known, but it bears reminding that, work always takes longer than expected to finish. Having minute sheets with deadlines for small sections of the project helped, but did not entirely mitigate this.

The delayed finishing of tasks appeared to be caused by one main factor: people's enthusiasm in saying they will do a task during a meeting tends to wane by the time they have to do said task - often ending up in tasks not done or done to less than their full potential. This resulted in other group members having to pick up the slack of those who did less work. Even during meetings, people's enthusiasm varied. It was new to me to have some team members playing on their phones when the rest of us were working.

It was evident that scope of the number and interconnectedness of subsystems meant that affecting one aspect of the system had knock-on effects on many other aspects. For instance, in order to increase the number of people in a vehicle, the length could be increased. This meant that stations would have to be longer to allow all passengers to get on/off. It also meant that the radii of curves in the loop of the track would have to be increased. This would increase the amount of track used and the time it took for each section to be travelled by vehicle, affecting the wait time at stations (and so on…). As a result, it seemed necessary to design in small iterations, changing one feature, then seeing how that affected the rest, and repeating until the best parameters were found overall. The house of quality helped reduce the number of iterations required, by making explicit the relationships between variables.

Cause for optimism came from the apparent potential for innovation in improving large, complicated systems, using methodologies such as TRIZ. This can allow some systems to remove unnecessary and costly elements, reducing overall system complexity.