An Objective Assessment of Accessible Routes for Manual Wheelchair Users on a University Campus

A Research Report presented in partial fulfilment of the requirements for the degree of

Master of Construction

in

Quantity Surveying

Massey University, New Zealand

2020

STATEMENT OF ORIGINALITY:

Title: An Objective Assessment of Accessible Routes for Manual Wheelchair Users on a University Campus.

I hereby declare that this report was written by me and it is a record of my own research work. It has not been presented before in any previous application for a degree. Reference made to all published literature have been duly acknowledged within the report.

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ACKNOWLEDGEMENTS:

I would like to express my sincere gratitude to my supervisor, Dr. Claire Flemmer, for her guidance and encouragement throughout the research. She ensured my research is on the right track and shared her thoughtful advice supportively. The details in her feedback have been insightful and motivated me to keep improving. I am deeply grateful for all her help and support.

I would also like to thank Mr. Chris Chitty for providing a great help to my research. The experiment could not be performed without his help with the equipment.

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ABBREVIATIONS:

C_{rr}	: Coefficient of rolling resistance
J	: Joules
MWC	: Manual wheelchair
N	: Newtons
NZBC	: New Zealand Building Code

AN OBJECTIVE ASSESSMENT OF ACCESSIBLE ROUTES FOR MANUAL WHEELCHAIR USERS ON A UNIVERSITY CAMPUS

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Disclaimer – All reports have been submitted as partial fulfilment for the project requirement for the Master of Construction degree.

ABSTRACT

Navigating in the built environment is essential for participating in daily activities. While most people use traditional wayfinding systems to find the fastest route, manual wheelchair (MWC) users need a more comprehensive system that captures the accessibility of the route and the physical effort required to use it as they face enormous challenges when navigating the built environment. This research evaluates a case study of a sample of routes on the Massey University East Precinct campus and provides an objective assessment of the accessibility of indoor and outdoor paths for MWC users. It develops a method for assessing the energy cost of each route using the rolling resistance of a weighted MWC. This information is presented on a map showing the directional energy cost in a colour-coded format for easy understanding. Features on the sample routes such as slope, cross-slope and doorways are assessed for their compliance with the New Zealand Building Code. The non-compliant features are also included on the map since they represent particular challenges to MWC users. The map is supplemented by navigation plans which provide directions of the routes and the description (such as slope and surface materials) of different parts along these routes. The method was determined to be statistically reliable as it reflected a higher rolling resistance on (i) rough surfaces, (ii) sloped surfaces and (iii) when the weight increased. It provided a true representation of the energy required to propel on different paths for the MWC users. The research also highlights features of the built environment which need to be addressed in order to improve MWC user accessibility. Chief among these, is the need to plan for practical alternative route when a path is temporarily blocked for maintenance and to focus efforts on removing the non-compliant sections of the routes.

Keywords: Accessible route, Manual wheelchair, Rolling resistance, Wheelchair navigation

1. INTRODUCTION

1.1 Background information

Navigating in a built environment is an integral part of daily life for the general public as they carry out ordinary tasks. While it may seem normal for most people to get around at their own pace, the manual wheelchair (MWC) users are significantly disadvantaged when navigating in the built environment due to the obstacles to wheelchair propulsion. The World Health Organization (2011) noted that a person's environment has a high impact on their health and the level of disability, as a result of the dynamic interaction between personal and environmental factors. In the case of MWC users, physical barriers (such as a rough floor surface and steps) can create difficulties ranging from inconvenience to complete inaccessibility which can limit their social participation. The decreased mobility may bring secondary negative impacts including the risks of mental stress, depression and cardiovascular disease, which lead to poorer quality of life and overall health.

Approximately 90% of all wheelchairs are manual pushrim propelled wheelchairs, where the users grasps, pushes and releases the pushrims (or handrims) to self-propel (van der Woude et al., 2001). Pushrim propulsion is inefficient and physically straining. Only 20% of each stroke cycle is effective in pushing the wheelchair forward. The remaining parts of the stroke cycle is the 'recovery' phase of positioning the arms for the next cycle (Flemmer & Flemmer, 2015). The propulsion is even more demanding in difficult footpath conditions, such as inclined surface (when wheelchair tends to move backward) and cross-slope (when wheelchair casters tend to turn downslope), which require a higher level of muscle activity to manoeuvre as compared to a flat surface (Holloway et al., 2015). A built environment with such demanding conditions can cause physical and mental discomfort to the MWC users in their daily lives.

In order to pre-plan trips in an unfamiliar environment, most people use navigation apps (such as Google Maps) to search for the directions. These apps can generate the shortest routes and different transportation options. However, they may not be useful for MWC users as their priority is to find an accessible route that they are able to use safely (Palazzi et al., 2010). The degree of accessibility of a path depends on the individual MWC user's capability due to their individual strength and health condition (such as tetraplegia and paraplegia). When manoeuvring along a path requires more energy than a MWC user can provide, that part of the built environment becomes inaccessible for that person (Cepolina & Tyler, 2004; Tyler, 2011). Therefore, MWC users would need a comprehensive wayfinding system that considers more than just the time and length cost and includes other factors such as the required physical effort of using the routes (Siriaraya et al., 2020).

Some researchers have examined the level of accessibility in the development of navigation apps by asking the MWC users to rank the condition and the level of difficulty of the routes. However, this subjective approach will not be applicable for MWC users with different capabilities (Neis, 2015). Other researchers have studied the energy use for MWC users doing specific tasks (such as driving up ramps of different gradients) but these studies were limited to the pre-designed laboratory settings. No studies have assessed route accessibility in terms of the energy required for a MWC user to navigate the route in a real- world environment and this is the research gap that is addressed in this research.

MWC users have a wide range of impairments, physical strengths and skills and therefore they have a wide variation in perceived level of difficulty when navigating the same path. Employing users' experiences as input to an assessment of the built environment accessibility would be subjective and dependent on their individual impairment (Lau et al., 2016). Therefore, an objective assessment of building accessibility, without personal user factors, would provide more consistent, independent and reliable information for wheelchair users seeking to navigate between places. It could also be used to target areas where universal design could be used to improve accessibility in the built environment.

1.2 Research aim and objectives

This project is focused on the accessibility of manual wheelchair (MWC) users in the built environment. The aim of the research is to conduct an objective assessment of the accessibility of indoor and outdoor routes for MWC users on the East Precinct campus of Massey University. The research questions are:

- What campus facilities would a student in a manual wheelchair need to access and what paths (indoors and outdoors) would they need to use to get to these facilities?
- On the paths, what barriers would impede manual wheelchair users?
- How much effort is required for a manual wheelchair user to navigate on the paths around campus?

Accordingly, the following five objectives are set to answer the questions and achieve the aim.

- To identify a sample of facilities a student would need to access on the East Precinct campus and to determine accessible routes (indoors and outdoors) for wheelchairs in order to access these facilities.
- To evaluate the properties and obstacles along the sample routes.
- To measure the rolling resistance of a manual wheelchair and compute the energy cost of using each accessible route in a manual wheelchair.
- To present the relative ease of navigating each accessible route.
- To produce a navigation plan with detailed accessibility descriptions of the sample routes.

The research will contribute to the extensive body of knowledge examining the accessibility of the built environment for MWC users. It will also develop a new, quantitative method for assessing route accessibility and an initial dataset for the East Precinct campus for potential expansion of similar studies, navigation planning or building design considerations.

Because this study demonstrates objective information on the accessibility of paths, it will not use subjective opinions or human participants in the path-evaluation processes. The experimental method is explained later in the proposal. The following boundaries are set to focus on the aim of the research:

- The research will focus on manual wheelchair users and will not cover those using motorized wheelchairs and other aided mobility (such as crutches and walking frames).

- The accessibility assessment will be independent of (i) the MWC users' individual health and disabilities (such as paraplegia and tetraplegia and (ii) the MWC users' positional adjustment (such as shifting their weight back when tilting their MWC to climb an incline).
- Only one type of MWC will be used for the experiment.
- Weather conditions (such as wind and rain) will not be taken into account.

The research is limited to a case study (selected routes on the Massey University East Precinct campus) and is limited to the conditions of those routes. It is recognized that general routes will have conditions (such as steeper slopes and cross-slopes, different surface types, etc.) that are not tested in this research. However, the method that is developed can be applied to other routes.

2. LITERATURE REVIEW

2.1 Standards for accessible design

In making the built environment more accessible to MWC users, there are several relevant mandates in New Zealand such as the New Zealand Disability Strategy 2016-2026 that encourages the organization to provide access to all places with ease and dignity (Office For Disability Issues, 2016) and the Building Act (the mandatory building legislation) that requires all buildings to provide access to people with disabilities. The building control framework in New Zealand consists of three main parts, namely, (i) the Building Act, (ii) Building Regulations and (iii) Building Code. These form the legislation framework to control the performance of buildings and encourage better practices in building design (Ministry of Business, Innovation and Employment, 2014). The Building Act mandates the buildings to comply with the performance standards set in the New Zealand Building Code (NZBC), which includes the minimum standards for providing access to buildings in the clause D – Access. In other counties, similar standards are applied under their local regulations, for instance, the American Disability Act (ADA) Standards for Accessible Design in the United States (Department of Justice, 2010) and Approved Document for Part M of the Building Regulations (Access to and use of buildings) in the United Kingdom (Ministry of Housing, Communities and Local Government, 2015).

The NZBC provides flexibility for innovative designs to meet or exceed the minimum standards. One way for the designers or property owners to demonstrate the compliance with the NZBC clause D – Access is following the practical guidance set in the 'NZS4121:2001 Design for access and mobility – buildings and associated facilities" (Standards New Zealand, 2001). In the standard, an accessible route is defined as an access route usable by people with disabilities to carry out normal activities and processes within the building. It shall be a continuous route that can be negotiated unaided by a wheelchair user and shall extend from street boundary or car parking area to the spaces required to be accessible. The requirements for accessible route and considerations for wheelchair accessibility are specified throughout the document. The relevant requirements are summarized in Table 1.

Features	Requirement in NZS4121:2001
Slope	The maximum allowable gradient is 1:12
Cross-slope	The maximum allowable gradient is 1:50
Clear width of accessible path	At least 1200 mm
Clear width for two wheelchairs to pass comfortably	At least 1800 mm
Clear opening of door	At least 760 mm
Car park surface	Stable, firm, slip resistant level surface (flatter than 1:50)
Thresholds	Thresholds should be level if possible, otherwise, contrast strips should be provided for change in level of 20 mm or less and a ramp should be provided for change in level greater than 20 mm

Table 1: Accessible design standards in NZS4121:2001.

Although there is a voluminous legislative framework to regulate the building design, the urban environment is usually designed and built according to the norms that exclude people with physical disabilities. Previous studies showed that even a built environment with a high compliance with the building accessibility standards, these minimum requirements are not meeting the need of all individuals (such as MWC users) because the disconnection and the difficulty of using the routes have been a serious problem for manoeuvring MWCs (Bills, 2017; Orellana et al., 2020). Jackson (2018) suggested that building practitioners must engage to understand to diversity of lived experience from disabled people to rectify the impediments in built environment. The compliance with legislation or building code should not be taken as tick-box checklist and assumed to be sufficient to fit the diverse needs and human rights. Instead, attention should be raised to the models, legislations and assessments of building accessibility and their interactions to lived experiences of disabled people in order to make improvements at a larger scale. The ultimate goal of a successful universal design (or a fully inclusive design) is the integration of accessible design into the main environment to reduce feelings of segregation by the users. Although the accessibility disparity between the people with disabilities and those without disabilities is likely to exist, this disparity should be minimized to promote an inclusive environment by removing the obstacles in the built environment (Vale et al., 2017).

2.2 Difficulties of using a MWC in the built environment

Meanwhile, it is not easy to provide a built environment that fits all different types of disability, such as motor, visual and hearing disabilities (Gamache et al., 2020). For instance, a well-defined curb can be helpful for people with visual disabilities to recognize the edge of a sidewalk (and road) but impose difficulty for wheelchair users to access the sidewalk. It is even harder when the it is designed by people without disabilities and the actual needs and difficulties of people with different impairments are not considered thoroughly. Therefore, when negotiating in the existing built environment, MWC users still face physical obstacles such as slopes, kerbs, rough surface types and poor surface quality. Each type of these obstacles hinders the MWC propulsion at a different extent. According to Matthews et al. (2003), the rank order of the barriers (from highest to lowest level of impedance) is: steps, high kerbs, deep gutters, lack of dropped kerbs, narrow pavements, steep gradients, adverse cambers, poor pathway maintenance and cobbled surfaces.

Manual wheelchair propulsion is physically demanding and often creates upper extremity overuse injuries and pain among MWC users, especially in the susceptible muscles group around their shoulders (Rankin et al., 2011). The barriers in the built environment often restrict and discourages wheelchair users from participating in diverse activities. It has been found that higher levels of physical barriers were associated with lower levels of social participation by wheelchair users (Smith et al., 2016). The limited mobility and tendency to stay at home are detrimental to their cardiovascular system and rehabilitation. It could also develop stress and social isolation, which lead to poorer quality of life (Chang et al., 2012; Chow & Levy, 2011).

2.3 Navigation in the built environment for MWC users

When visiting an unfamiliar place, the MWC users have to pre-assess the routes and the surrounding environment to avoid the unexpected obstacles. Occasionally, MWC users can use some simple methods such as talking to others who are familiar with the destination (Hara et al., 2016). However, most people are not wheelchair users and may give a 'misdirection' as they are not attentive to the barriers to wheelchair movement such as a narrow pavement, street furniture and sign posts (Tannert et al., 2019). Therefore, the MWC users may also cross-check the routes with the online navigation systems such as the Google Maps.

Traditional navigation systems tend to focus on identifying the shortest or fastest routes for the users. These routes are often generated based on the length and time cost, while these may not be the only concerned factors to the MWC users. Siriaraya et al. (2020) suggested that other route quality attributes, including safety and effort, should be introduced to the development of a comprehensive navigation system. The systems that focus on the effort quality aim at reducing the cognitive effort or the physical effort when travelling between two points. These systems tend to consider the internal factors of the user in relation to the environmental factors in order to reduce the burden of navigation for specific groups. One way to evaluate the interaction between the user and the environment is comparing the 'provided capabilities' of the user and the 'required capabilities' for undertaking a given task in the environment (Tyler, 2011).

2.4 Current studies on wheelchair navigation systems

Previous researches on wheelchair navigation systems have used Geographical Information (GIS) systems to identify the physical barriers of routes, such as Modelling Access with GIS in Urban Systems (MAGUS) (Matthews et al., 2003), U-Access (Sobek & Miller, 2006), Path 2.0 (Palazzi et al., 2010) and Map for Easy Paths (MEP) (Comai et al., 2017). Using the physical features of routes, they generate the accessible routes for wheelchair users showing the shortest routes to avoid obstacles between two locations with the aim of requiring a lower level of difficulty, less time and less energy from users.

The concept of personalized accessible routes emerged as a way to include user's personal preference in the navigation system. Personalized Accessible Maps (PAM) (Karimi et al., 2014) and mPASS (Prandi et al., 2014) used individual needs in generating accessible routes planning. Considering the varied types and degrees of the users' strength and impairment, weighting the accessibility parameters according to the user's personal preference was aimed to produce more individually suitable routes for the users. These routing systems have used geographical factors to generate the accessible routes for the wheelchair users to pre-plan their trips. The routes are generated by calculating the 'impedance score', which is affected by subjective weightings of the obstacles (such as rating of surface roughness). Different systems or studies use different approaches to the weightings of the parameters based on the survey or individual user requirements (Neis, 2015). Therefore, the information on accessibility is inconsistent. The accessibility parameters in the routing systems may not fit the variety of wheelchair users' capabilities. In real-world situations, errors may arise from overestimating and underestimating the capabilities for overcoming the obstacles. The errors would result in additional distance or impassability in the suggested routes (Tannert et al., 2019).

The previous studies are valuable to evaluating accessibility for wheelchair navigation. However, the subjective ranking of accessibility may not be useful for MWC users with different capabilities. There is also a lack of consideration to the energy requirements of using the routes in a 'real-world' environment. No studies have assessed route accessibility in terms of the energy required for a MWC to navigate the route and this is the research gap that is addressed in this research.

2.5 Rolling resistance in manual wheelchair propulsion

According to van der Woude et al. (2001), the power balance of wheelchair propulsion is influenced by (i) rolling resistance, (ii) air resistance, (iii) internal friction and (iv) slope and acceleration. The power balance equation explains that in order to maintain the speed of the wheelchair-user combination, a certain amount of external power is required from the MWC user to overcome the energy losses in the system. Rolling resistance is the force that resists the motion of a body rolling on a surface (i.e. resists the motion of the MWC user in wheelchair propulsion). At low and constant speed (around 1 ms^{-1}), it becomes the major source of energy loss during wheelchair propulsion since the other resistive forces (such as bearing resistance and air drag force) are negligible (Lin et al., 2015; van der Woude et al., 2003). It has also been found to have a strong correlation with the perceived effort of the MWC users (Brubaker, 1986; Matthews et al., 2003). Therefore, rolling resistance is a reliable indicator of the energy cost of manoeuvring a MWC. It can then be used in a quantitative approach to calculate the best route in navigation systems (Duvall et al., 2016; Kasemsuppakorn & Karimi, 2009; Matthews et al., 2003; Sumida et al., 2012).

To evaluate the energy cost of MWC propulsion, previous studies have done tests in laboratory settings, measuring aspects such as drag force on a treadmill and propulsion force on inclined surfaces with the pre-set slope angles (Gagnon et al., 2014; Holloway et al., 2015). From these studies, it was found and confirmed that certain situations (such as higher slopes) require more energy and effort from the MWC users to propel. However, it cannot be applied to the navigation in the real-world environment because the previous studies are limited to the settings of the test, for instance, the treadmill belt as the only tested floor surface. It is unable to evaluate the real environmental conditions faced by the MWC users in their daily lives (e.g. different floor surfaces). Hence, in this research, the field experiment is conducted in real paths that MWC users would need to navigate on the campus.

3. RESEARCH METHODOLOGY

3.1 Research approach

A quantitative method is used in this research in order to generate numerical data on route accessibility so that routes can be easily compared in terms of level of difficulty. To collect the quantifiable data, this research uses an objective approach to the accessibility assessment with an experimental method. According to Lau et al. (2016), the qualitative methods in building accessibility assessment often result in varying and inconsistent information from the subjective opinions. MWC users have a wide range of impairments (such as tetraplegia and paraplegia) and health conditions (such as upper body strength) and therefore, they have a wide variation in perceived level of difficulty when navigating the same path. In order to provide reliable information, subjective opinions or users' experiences should be avoided in accessibility assessment. Instead, an experimental measurement can provide a more consistent and standardized method to reflect the accessibility of the built environment for all MWC users. Without the participation of MWC users, the experiment will simulate the user by using stones to replicate a person's weight in a wheelchair and by pulling the wheelchair to drive the movement along the paths.

3.2 Sample routes

Since Massey University's East Precinct campus does not have a well-organized accessibility map for MWC users, it was chosen as the location to trial the experimental determination of the accessibility of the area. A sample of indoor and outdoor routes were chosen for this research, based on the places a student in a MWC would need to access whilst on the campus. These places include carpark, library, lecture rooms, toilets, recreation centre, campus information services, student accommodation, café, staff offices and student centre. Accessible routes connecting these places should be provided to allow MWC users to access to these facilities. These routes are used as representative samples to assess the accessibility of the campus as summarized in Table 2 (the locations of the routes are shown in Appendix 2).

Route	Point A	Point B	Route length (m)	Indoor/ Outdoor paths percentage
1	Main entrance of Pukeko Hall (student accommodation)	Main entrance of Atrium Building	233.5	17% indoor, 83% outdoor
2	Atrium Building teaching room AT1	Main entrance of Massey Business School	252.1	34% indoor, 66% outdoor
3	Mobility carpark near the library	Side entrance of the library	52.9	100 % outdoor
4	Main entrance of the café	Main entrance of SNW lecture theatre	120.7	100% outdoor
5	Lecture room SNW200	Accessible toilet in SNW lecture theatre	30.4	100% indoor
6	Main entrance of SNW lecture theatre	Side entrance of the Recreation Centre	385.5	100% outdoor
	(During the experimental work, a temporary construction blocked a portion of Route 6.)			
7	Main entrance of Atrium Building	Main entrance of Mathematic Sciences Building	108.5	100% outdoor

**SNW refers to the building Sir Neil Water Lecture Theatres.*

Table 2: Summary of the sample routes.

These accessible routes include varied features that affect the accessibility and difficulty of using the routes, for example, travelling on levelled or sloped surfaces and on different surface finishes (such as carpet and outdoor tiles). These factors will affect the level of impedance and therefore, the features of each route should be evaluated. Based on the differences of features (such as changes from a level surface to a slope and changes of surface materials), the routes are broken down into segments (shown in Table 4). The rolling resistance of the weighted MWC was measured for each individual segment of a route and used to compute the overall energy requirement. Temporary features (such as a temporary work site) in the paths are also marked to recognize their effects on the accessibility.

3.3 Rolling resistance and energy cost

As discussed in Section 2, the rolling resistance of the weighted MWC is the primary cause of energy expenditure as bearing resistance and air resistance are proven to be negligible in daily locomotion (Lin et al., 2015; van der Woude et al., 2003). According to van der Woude et al. (2003), rolling resistance is defined as 'the required drag force that has to be exerted parallel to the floor surface in the line of coasting of the wheelchair'. It is expressed as:

$$F_{roll} = C_{rr} \times W \tag{1}$$

where F_{roll} is the horizontal force moving the wheelchair along the path, C_{rr} is the coefficient of rolling resistance (dependent on tire and floor characteristics) and W is the downward force of the weight of the loaded MWC due to gravitational acceleration.

The weight is calculated as:

$$W = m \times g \tag{2}$$

where m is the total mass of the loaded MWC and g is the gravitational acceleration (approximately 9.81 ms^{-2}).

When propelling up an inclined or sloped surface, the total drag force becomes:

$$F_{drag} = F_{roll} + mg \sin \alpha \tag{3}$$

where α is the angle of the inclination and F_{roll} and $mg \sin \alpha$ are the forces parallel to the floor surface. A diagram is shown in Figure 1 to illustrate the force components of an object (i.e. the wheelchair) on an inclined surface.

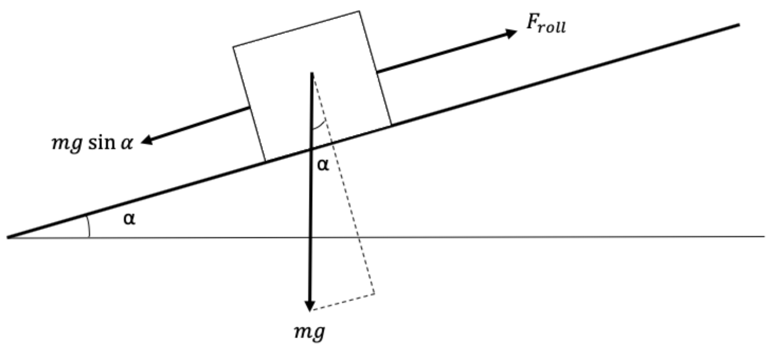


Figure 1: Forces on an inclined surface (slope shown exaggerated).

The value of rolling resistance (F_{roll}) is used to compute the energy cost (E) of maneuvering the wheelchair along the segment, using the equation:

$$E = F_{roll} \times d \quad (4)$$

where d is the distance of the displacement and F_{roll} is the force required to move the wheelchair along the segment. The total energy cost of each route is the sum of the energy cost of all segments in it.

3.4 Experimental Setting

A basic, self-propelled MWC was used in the experiment of measuring rolling resistance (Appendix 3 lists the MWC specifications). The wheelchair was loaded with 65 kg of coarse river stones to replicate the weight of a person (with 50 kg on the seat and 15 kg on the footrests). These weights form the total load on the MWC and was kept constant throughout all experiments on each segment.

One way to determine rolling resistance is using the pulling method to measure the reaction force when the rolling object is pulled (Chua et al., 2010; Wargula et al., 2019). In this research, a spring balance was used to measure the force required to move the wheelchair along the paths. The spring balance was hooked to one end of the two tie down straps (2m long), with the other end attached to the wheelchair (just above the seat). The spring balance readings (showing the reaction force) was recorded with a video camera to store the data.

The loaded wheelchair (attached with tie down straps and spring balance) was pulled manually along the segment to measure the rolling resistance in each segment (see Figure 2). The travelling speed was a slow walking pace (around 1 ms^{-1}) so that the air drag during the test is negligible. In an ideal situation, the pulling direction of the tie downs is perfectly horizontal and parallel to the floor surface, so that the reaction force for pulling the wheelchair (F_{roll}) can be measured directly from the spring balance readings. The sensitivity of the measurement to tie-down positions is shown in Appendix 4. The reliability and accuracy of the experimental method was checked by measuring one indoor segment and one outdoor segment several times and determining the statistical variation in the measurements. The validity of the experimental method for different weights was also checked by measuring the same segment with a range of weights (i.e. 55, 60, 65, 70, 75 kg) with an approximate weight distribution on the seat and the footrests.

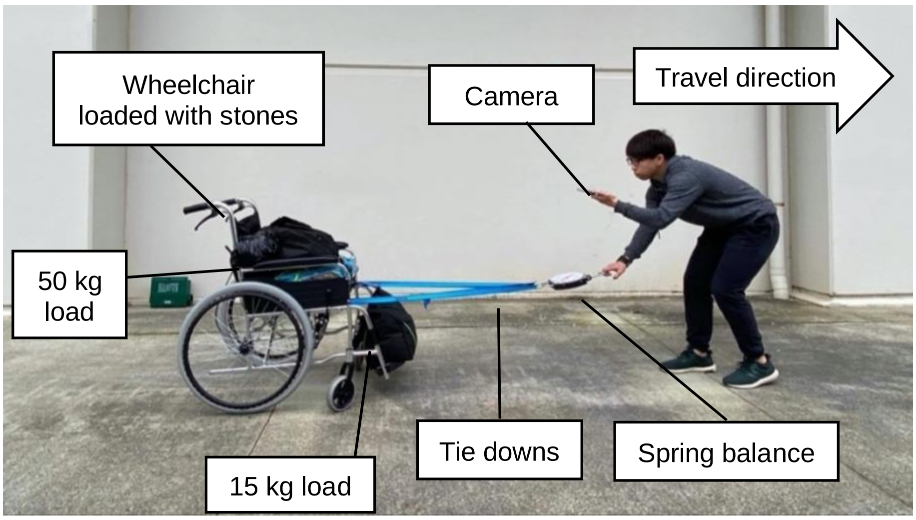


Figure 2: Illustration of the experimental setting.

The rolling resistance (F_{roll}) is the main variable to be collected in the experiment as it is used to compute the overall energy cost (E) of the routes. The values of F_{roll} and E are dependent on the building features (such as slope, distance and surface type). These building features are the independent variables in the experiment that form a treatment for each experimental unit (i.e. each segment). Another factor to consider is the velocity of the pulling movement, it was measured from the video clips to ensure a slow speed (around 1 ms^{-1}) for the air resistance to be negligible. Each segment has a different combination of these variables and they were collected during the experiment by using different equipment or method as summarized in Table 3.

Variables	Equipment/ Method
Rolling resistance	Recording the spring balance measurements with a video camera
Energy cost	Computing the measured rolling resistance and the distance of displacement
Path lengths; door widths	Taking measurements with a tape measure
Slope (parallel to the travel direction); cross-slope (perpendicular to the travel direction)	Using the digital slope measurer and spirit level to determine the gradients and the direction of slopes
Velocity of the wheelchair movement	Dividing the distance travelled by the time period from the video recordings
Door types; floor surface materials; physical obstacles (such as a high kerb)	Obtaining information from the Massey University's Facilities Management or field observation

Table 3: Method of collecting the variables in the experiment.

4. RESULTS

4.1 Evaluation of the physical features in the sample routes

The sample routes that transit through the indoor and outdoor environment on the campus were evaluated by measuring their physical features with corresponding tools as summarized in Section 3. During the data collection, there was a significant barrier in one of the sample routes (Route 6) which was a construction work site blocking and disconnecting a part of the route. This route became inaccessible to wheelchairs and the data collection could not be carried out on this route. Hence, the data for Route 6 are not included in the following results. However, this highlights an important aspect of MWC accessibility, namely the need to minimize route disruptions.

For the rest of the sample routes, physical features (such as slope, cross-slope, clear path width and door width) were measured along the routes. According to NZS4121:2001, level surfaces include surfaces with a gradient flatter than 1:50 (i.e. 1.15 degrees) and the minimum clear width that allows two wheelchairs to pass comfortably is 1800 mm, which is 1.5 times of the minimum clear width of an accessible path (i.e. 1200 mm). Therefore, in this research, the segments with a slope smaller than 1.15 degrees are considered as level surfaces and the path clear widths that are greater than 1800 mm are marked as >1800 mm. As discussed in Section 3, the routes were divided into segments of approximately uniform rolling resistance (i.e. uniform slope and surface materials) as shown in Table 4. The highlighted cells in the table are the features that are non-compliant with the NZBC clause D1 Access Route (refer to Section 2.1). Likewise, Table 5 shows the doorways and the non-compliant features in the sample routes. Since the accessibility of a route for MWC users is also influenced by the physical facilitators and the barriers provided in the environment, these features from the sample routes are identified and summarized in Table 6.

Route	Segment	Slope (degree)	Cross-slope (degree)	Clear width (mm)	Floor surface materials	Route length (m)
1	1.1	0.3	0.8	>1800	Exposed aggregate concrete	233.5
	1.2	2.1	0.6	>1800	Exposed aggregate concrete	
	1.3	1.6	0.1	>1800	Sandstone concrete	
	1.4	0.0	0.1	>1800	Indoor smooth concrete	
	1.5	0.0	0	>1800	Indoor smooth concrete	
	1.6	0.3	0.7	>1800	Outdoor stone tile	
	1.7	2.2	0.2	>1800	Outdoor stone tile	
	1.8	3.4	0.5	>1800	Exposed aggregate concrete	
	1.9	0.3	0.7	>1800	Brickwork	
2	2.1	0.0	0.1	>1800	Indoor smooth tile	252.1
	2.2	0.0	0.2	>1800	Low-pile carpet	
	2.3	0.1	1.0	>1800	Brickwork	
	2.4	4.0	0.5	>1800	Brickwork	
	2.5	0.2	0.8	>1800	Brickwork	
	2.6	0.0	0.2	>1800	Indoor smooth tile	
	2.7	4.1	0.5	1530	Brickwork	
	2.8	2.2	0.9	>1800	Brickwork	
	2.9	0.4	0.8	>1800	Brickwork	
3	3.1	2.3	0.5	>1800	Asphalt	52.9
	3.2	7.8	0.4	1520	Exposed aggregate concrete	
	3.3	0.2	0.4	>1800	Exposed aggregate concrete	

4	4.1	0.3	0.7	>1800	Outdoor stone tile	120.7
	4.2	2.2	0.4	>1800	Outdoor stone tile	
	4.3	0.4	0.4	>1800	Outdoor stone tile	
	4.4	4.7	0.5	>1800	Exposed aggregate concrete	
	4.5	0.0	0.3	>1800	Outdoor stone tile	
5	5.1	0.0	0.2	>1800	Low-pile carpet	30.4
6	*Not available due to temporary work in the route*					
7	7.1	0.5	1.6	1660	Brickwork	108.5
	7.2	4.6	0.2	1200	Exposed aggregate concrete	
	7.3	0.2	0.4	>1800	Exposed aggregate concrete	

Table 4: Summary of physical features in the sample routes.
(Highlighted cells are the non-compliant features)

Route	Segment	Location	Door type	Door width (mm)	Thresholds
1	1.3	Entrance to Student Central	Automatic sliding door	1520	Threshold ramp: 150 mm long
	1.4	Accessible lift	Lift door	1100	Level
	1.5	Entrance to Student Central	Automatic sliding door	2400	Threshold ramp: 150 mm long
	1.9	Entrance to Atrium Building	Press button to open	960	Change in level: 18 mm
2	2.1	Accessible lift	Lift door	900	Level
	2.2	Corridor	Press button to open	970	Level
	2.3	Entrance to Atrium Building	Press button to open	1920	Change in level: 30 mm
	2.6	Entrance to Quad A Building	Automatic sliding door	2320	Level
	2.9	Entrance to Massey Business School	Automatic sliding door	2280	Level
3	3.3	Entrance to library	Kept open	2100	Change in level: 25 mm
4	4.5	Entrance to SNW	Press button to open	1760	Level
5	5.1	Entrance to accessible toilet	Pull manually	860	Level
6	*Not available due to temporary work in the route*				
7	7.3	Entrance to Mathematic Sciences Building	Automatic sliding door	1100	Level

Table 5: Summary of doorways in the sample routes.
(Highlighted cells are the non-compliant features)

Type of feature	Description of feature	Corresponding segment
Facilitators	Accessible lift	1.4; 2.1
	Automatic sliding door	1.3; 1.5; 2.6; 2.9; 7.3
	Accessible ramp	2.7; 3.2; 4.4; 7.2
	Accessible toilet	1.4; 2.2; 5.1
	Mobility carpark	3.1
Barriers	Bollards for guiding vehicles	1.8; 2.5; 2.8; 7.3
	Unlevel thresholds at entrance	1.9; 2.3; 3.3
	Street furniture (bench seats along the path)	7.1

Table 6: Physical facilitators and barriers in the sample routes.

4.2 Accuracy test

Before conducting the experiment on the sample routes, the accuracy of the experimental method was tested by running an accuracy test on an indoor surface and an outdoor surface of common floor materials. The materials of the two chosen flat surfaces were indoor smooth concrete and outdoor aggregate concrete. A 30 second test was repeated 8 times on each surface, using the same experimental set-up with 65 kg load on the MWC as discussed in Section 3. The force measurement was taken every second to generate 30 readings from each run. In total, there are 240 readings of rolling resistance from each of the indoor and outdoor surfaces. The data were statistically tested with IBM SPSS Statistics for Windows, Version 26.0. The results of the statistical tests are shown in Appendix 5. The results of the statistical tests showed that the data from all 16 runs are normally distributed and there is no statistical difference between the mean values of the 8 repeated tests on each surface, which confirmed the repeatability of the experimental method.

In order to determine whether the experimental method is valid for a range of weights, the accuracy test was also run using other 4 weights (i.e. 55, 60, 70, 75 kg) loaded on the MWC with an approximate weight distribution on the wheelchair seat and footrests. The rolling resistance of all 5 measured weights on the indoor and outdoor segments are summarized in Table 7. It is shown that on the same surface, the rolling resistance increased as the load on the MWC increased. According to the statistical test on these data, there is a statistical difference between these 10 groups of data (5 weights on each of the indoor and outdoor segment), which means using different loads on the MWC generated statistically different values of rolling resistance. The coefficient of rolling resistance (C_{rr}) is calculated from the rolling resistance and the total weight of the loaded wheelchair, which consists of the weight of the wheelchair (i.e. 12.55 kg) and the weight of the stones loaded on the wheelchair. Overall, the C_{rr} of the outdoor, rougher path (ranging from 0.0274±2.9% to 0.0356±1.5%) is higher than the C_{rr} of the indoor path (ranging from 0.0222±1.7% to 0.0296±2.3%) for all of the 5 measured weights (see Figure 3).

The results of the statistical tests showed that the experimental method has a high accuracy and can generate statistically reliable force measurement for every set of the experiment. Hence, the experiment was conducted once for each segment in the sample routes (with 65 kg load) for collecting the data.

Total load on MWC (kg)	Load on seat (kg)	Load on footrests (kg)	Rolling resistance on the indoor segment (mean ± relative standard deviation)	Rolling resistance on the outdoor segment (mean ± relative standard deviation)
55	12.69	42.31	14.7 N ± 1.7%	18.2 N ± 2.9%
60	13.85	46.15	16.4 N ± 3.4%	20.3 N ± 1.8%
65	15	50	17.3 N ± 1.6%	25.4 N ± 1.6%
70	16.15	53.85	23.0 N ± 2.5%	25.7 N ± 1.3%
75	17.31	57.69	25.4 N ± 2.3%	30.6 N ± 1.5%

Table 7: Rolling resistance measurement in the accuracy test.

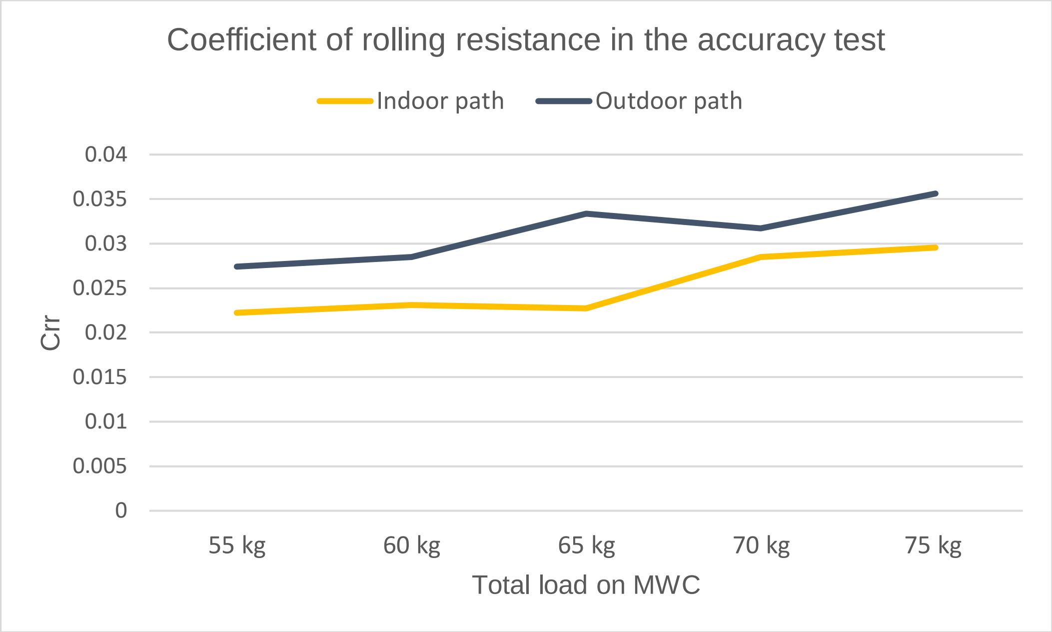


Figure 3: Coefficient of rolling resistance in the accuracy test.

4.3 Results of rolling resistance experiment

The experiment was conducted on each segment at a slow walking speed that ranged from 0.78 ms^{-1} to 1.26 ms^{-1}. On each sloped surface, a free-wheel test was carried out to check if the loaded wheelchair could roll down the slope on its own without any additional force. If the wheelchair could free-wheel down the slope, carrying out the experiment in the downhill direction would be unpracticable because the wheelchair would accelerate down the slope. Therefore, the experiment was conducted in the uphill direction to collect the data for that segment.

A video camera was used to record the spring balance, which showed the rolling resistance for pulling the MWC throughout the experiment. From the video clips, the spring balance reading was taken every second to collect the values of rolling resistance along the paths. The rolling resistance is influenced by the properties of each segment (such as slope and surface materials) and independent of the travelled distance. The average rolling resistance for the indoor paths and outdoor paths are shown in Figure 4 and Figure 5 respectively.

For indoor paths, the results showed that the segment 1.4 (smooth concrete) has the lowest rolling resistance of 18.2 N and the segment 5.1 (carpet) has the highest rolling resistance of 24.5 N. For outdoor paths, the segments are separated into level and sloped surfaces. For level outdoor paths, the segment 1.6 (stone tiles) has the lowest rolling resistance of 18.0 N and the segment 1.9 (brickwork) has the highest rolling resistance of 33.0 N. The results also showed that the sloped surfaces have higher values of rolling resistance than all level surfaces. Comparing the segments within the same group of surface material, it is shown that sloped surfaces have much higher rolling resistance, which indicated that it is harder to propel up the slopes. Among all the indoor and outdoor paths, segment 3.2 (exposed aggregate concrete, 7.8 degree slope) has the highest average rolling resistance of 124.9 N, which is around 6.8 times more than that on a smooth, level surface.

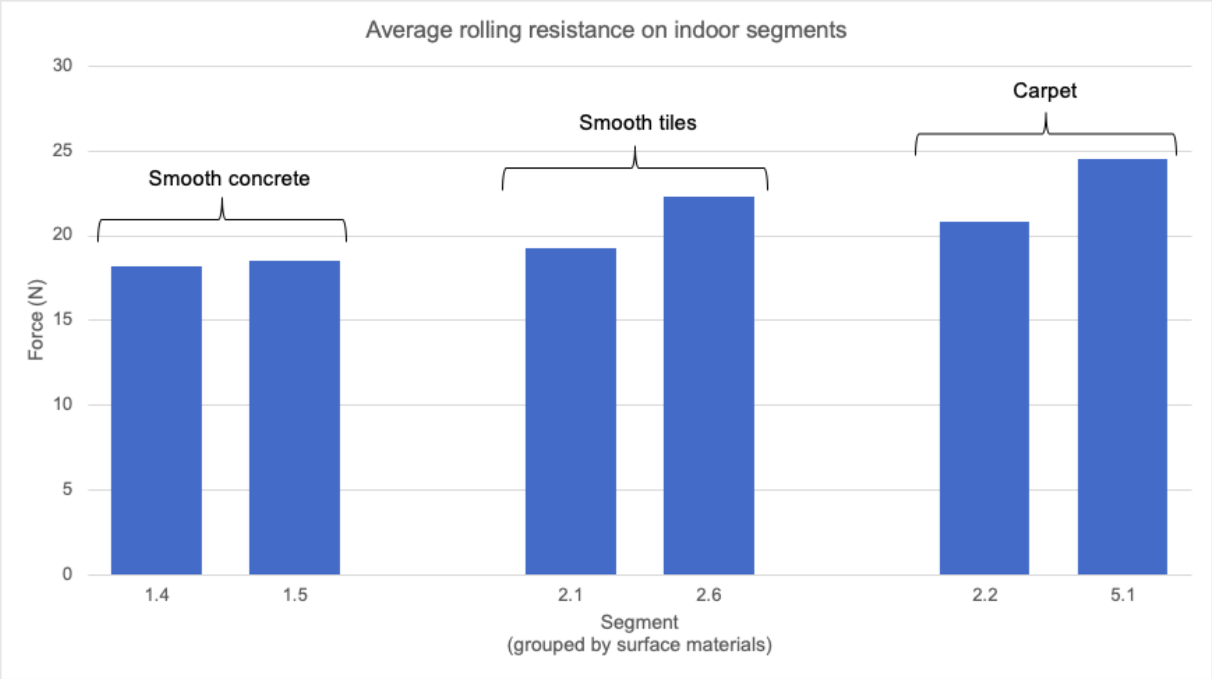


Figure 4: Average rolling resistance on indoor segments.

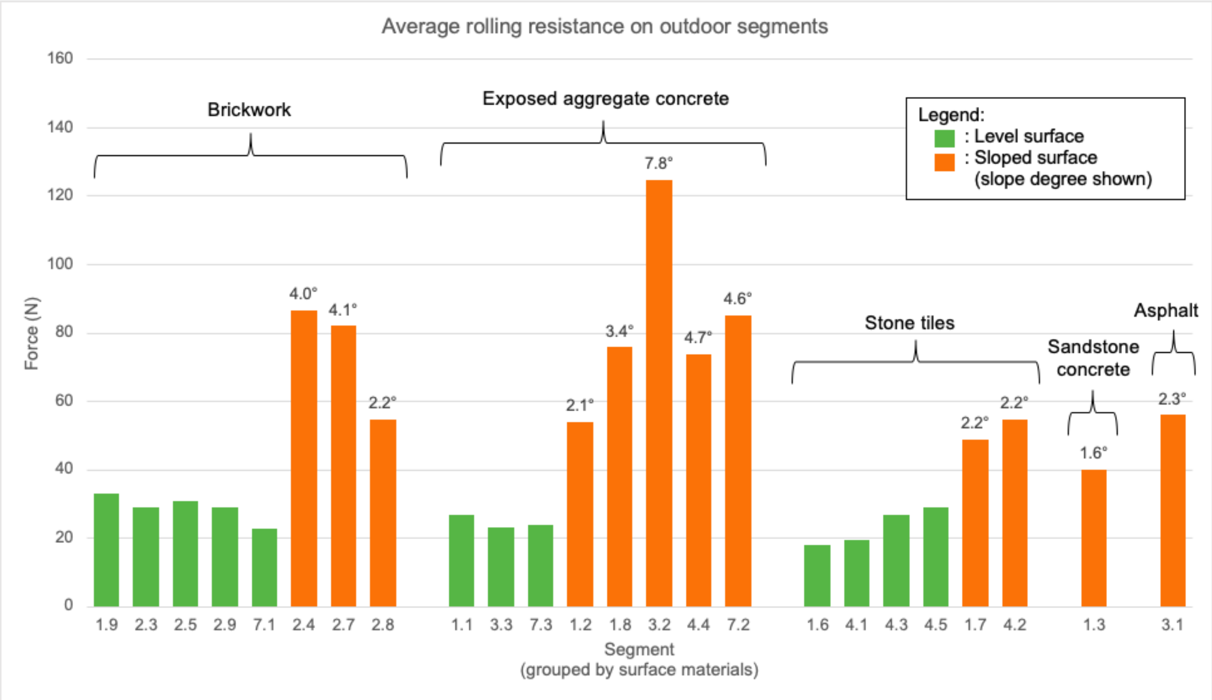


Figure 5: Average rolling resistance on outdoor segments.

The rolling resistance data were also used to generate a scatter plots graph for each segment, with a trendline of the plots to show the overall pattern of the rolling resistance along the travelled distance in that segment. An example is given in Figure 6 and the data for all segments are shown in Appendix 6.

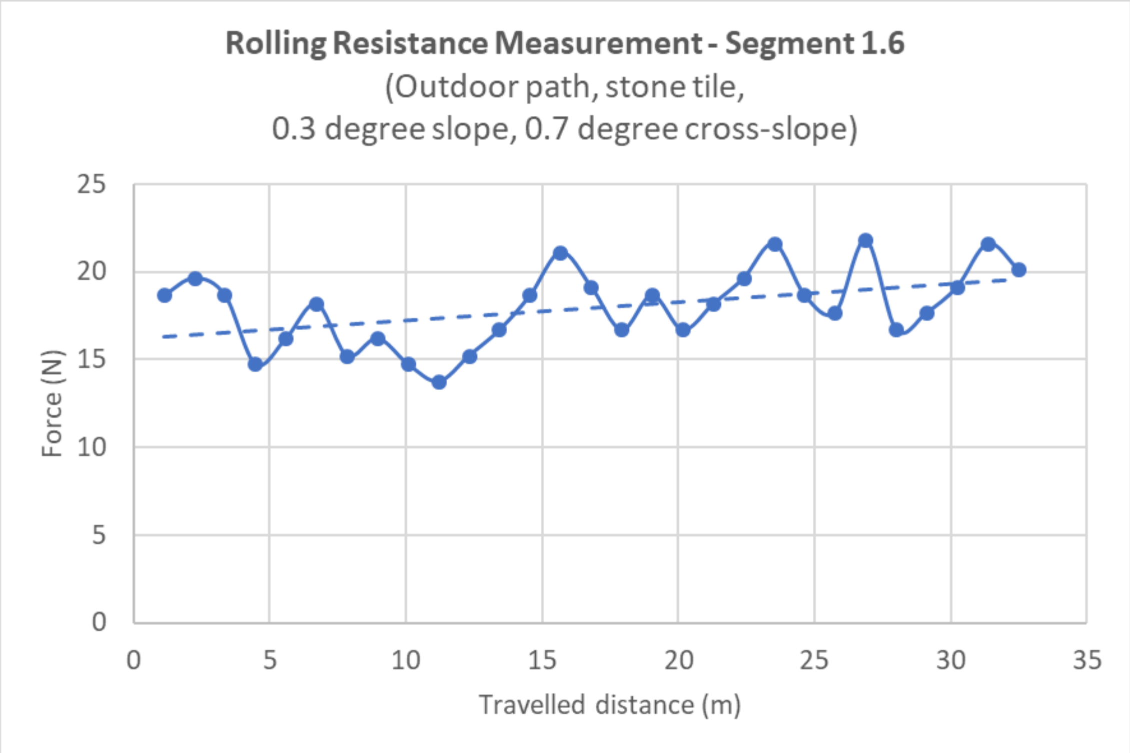


Figure 6: An example of the scatter plots graph (with a trendline) of the rolling resistance measurement in segment 1.6.

4.4 Total energy cost of using the sample routes

Using the rolling resistance measurement, the corresponding force on the trendline was used to compute the energy cost for the smaller parts in the segment. The energy cost (unit: Joules/ J) was computed with the formula:

$$E = F_{roll} \times d \qquad (5)$$

where F_{roll} is the force (N) from the trendline and d is the travelled distance (m) of each smaller part in the segment.

The segmental energy cost of the indoor paths and outdoor paths are shown in Figure 7 and Figure 8 respectively (exact values shown in Appendix 7). As the equation (5) provides, the energy cost is influenced by the segment length. It is reflected in the results that the energy cost of segments with similar average rolling resistance are different due to the travelled distance. For example, the segments 1.4 and 1.5 are both level paths on smooth concrete and have similar average rolling resistance (refer to Figure 4) but the length of these two segments are 28.5 m and 10.3 m respectively. By using the equation (5), the segmental energy cost of the two segments are 522 J and 191 J for segment 1.4 and 1.5 respectively as the longer travelled distance (on the same surface material) produces a higher energy cost.

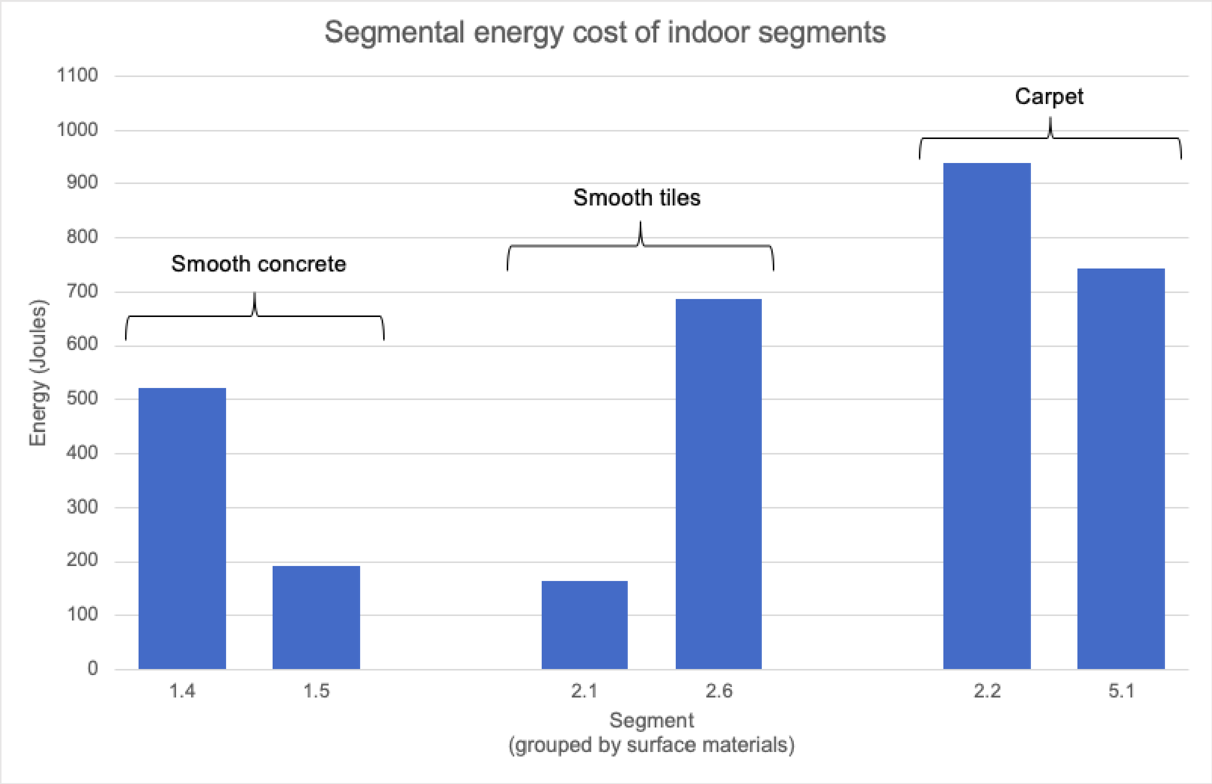


Figure 7: Segmental energy cost of indoor segments.

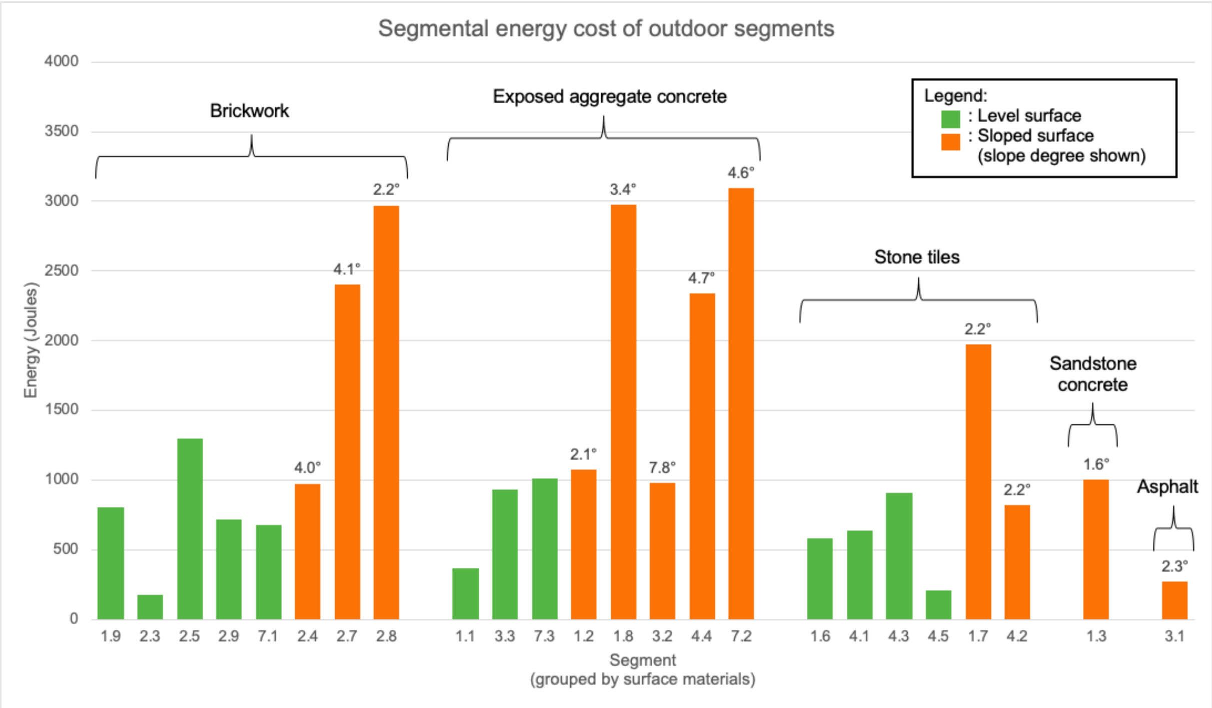


Figure 8: Segmental energy cost of outdoor segments.

The total energy cost of using each route is sum of all the involved segmental energy cost in it. Since these segments include both level and sloped surfaces, the travel direction needs to be considered when computing the energy cost for the sloped surfaces. If the wheelchair can free-wheel down the slope, a MWC user would not need to push to move the wheelchair in this travel direction. Thus, the energy cost for that segment (with a sloped surface) is assumed to be 0 J when computing the total energy cost. Any free-wheeling beyond the bottom of the slope is assumed to be negligible. Among the measured sloped segments, with the slope angle ranging from 1.6 to 7.8 degrees, the wheelchair could free-wheel down on each of the sloped surfaces from a static position and therefore, the energy cost is 0 J in the downhill direction. By considering both travel directions of the sample routes, the total energy cost for each route is shown in Figure 9.

The data showed that when using the sample routes in the direction of going from Point A to Point B, Route 5 (a 30.4m long indoor path on low pile carpet) has the lowest energy cost (744.3 J) and is relatively the easiest route while Route 2 (a 252m long path with 34% indoor and 66% outdoor portions; 38% sloped surfaces) has the highest energy cost (4954.2 J) and would be the hardest route for MWC users. Considering the opposite direction of the sample routes (going from Point B to Point A), the energy cost of Route 5 remains as the lowest with the same energy cost as the only segment in the route is level. The energy cost of Route 2 also remains as the highest but the energy cost is increased to 9352.4 J in this travel direction. This significant difference in the energy cost between the two travel directions is due to the effect of the sloped surfaces in the route. When going from Point A to Point B in Route 2, energy cost of two sloped surfaces in the route are taken to be 0 J as the wheelchair can free-wheel down the slope. On the other hand, going up these two sloped surfaces contributes 5371.3 J to the total energy cost of the same route in the opposite direction (from Point B to Point A). Similarly, the energy cost of other sample routes with sloped surfaces changed when travelling in the opposite direction based on the direction of the slopes. For instance, it takes 4789.1 J to use Route 7 when going from Point A to Point B, which is more than double of the opposite direction (1693.5 J) where the MWC user can free-wheel down the ramp in that route.

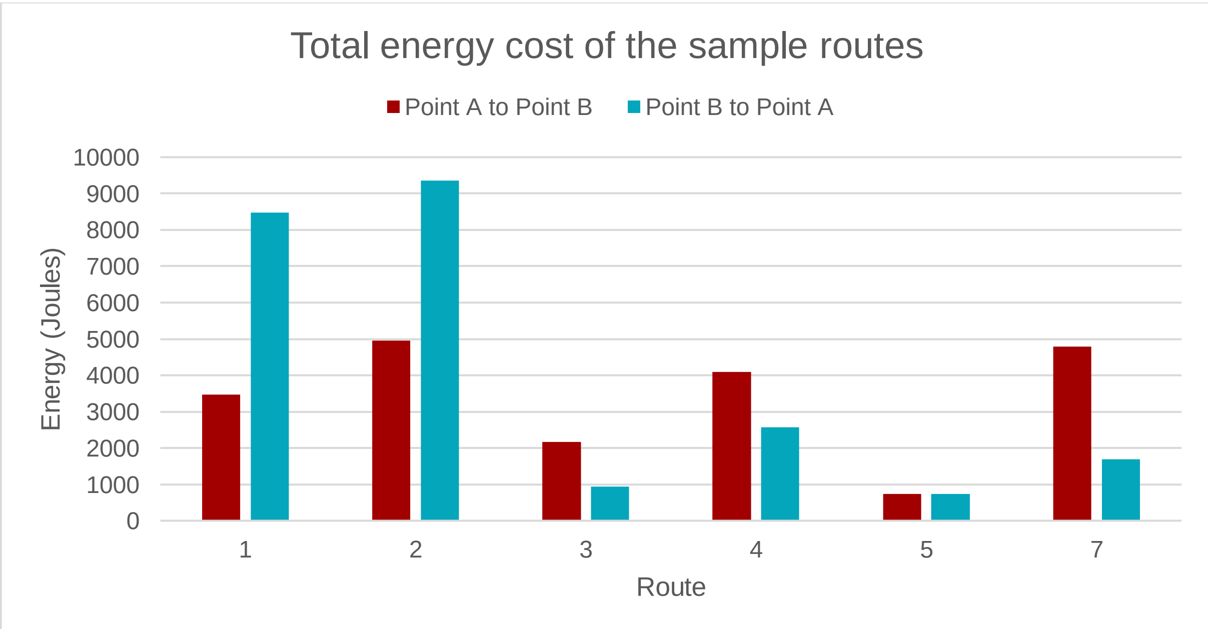


Figure 9: Total energy cost of each route.
(Route 6 is not included due to temporary work in the route)

4.5 Navigation plan for each route

Traditional navigation systems tend to focus on generating the routes based on the length and time cost, while the MWC users would also consider other attributes of the routes such as safety and effort as they navigate around the campus (Siriaraya et al., 2020). In this research, the navigation plans for each route are generated to provide the information that a MWC user would need when using the sample routes on campus. Each navigation plan consists of two parts, namely (i) the directions/ instructions that guide the way and (ii) the campus map that shows the route.

The directions provide the instructions for moving along the accessible route in both travel directions (going from Point A to Point B and vice versa) to prevent the MWC users from going to an inaccessible path. It also provides the energy cost of using each part of the route (based on the experimental results) and the information of the physical features of the route to give the user a better illustration of the path. Depending on the condition in each part, these physical features include the floor materials, slope and doorway. At the same time, the route is shown on the campus map like normal navigation systems with small arrows indicating the travel direction. On the map, the arrows are colour coded in green, yellow or red to represent the accessibility level of that part of the route based on the computed energy cost. These levels were generated from the results of the energy cost of the 30 segments measured in this research, which were divided into 3 groups to correspond the 3 accessibility levels (see Appendix 8). In the colour coded routes, green represents the paths that are reasonably comfortable to use (energy required is below 684 J), yellow represents semi-comfortable (energy required is between 684 and 989 J) and red represents uncomfortable (energy required is greater than 989 J). The features that are non-compliant with the NZBC is marked on the map with a warning sign and a short description as these features are physically demanding for the MWC users. Table 8 shows the overview of the campus map and the map key used in this research. The navigation plans and the directions for each of the sample routes are shown in Table 9 – Table 14.

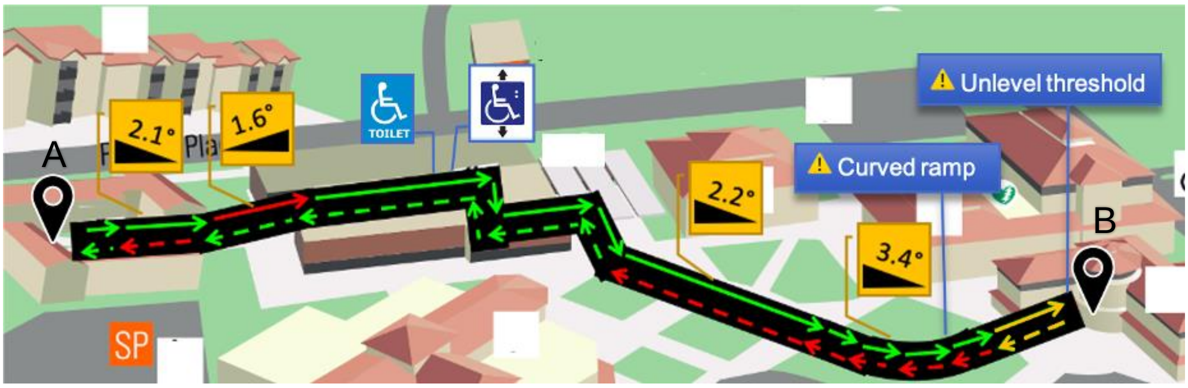
Overview of the Massey University East Precinct campus (Massey University, 2020)


Map key in this research (different to the original key on the campus map)	
	: Accessible lift
	: Accessible toilet
	: Gradient and direction of slope
	: Features not complied with NZBC
	: Point A/ B of the route
	: Travel direction from A to B
	: Travel direction from B to A

Table 8: Overview of the campus map and map key.

Route 1 (233.5m, 17% indoor, 83% outdoor)

Point A: Main entrance of Pukeko Hall
Point B: Main entrance of Atrium Building



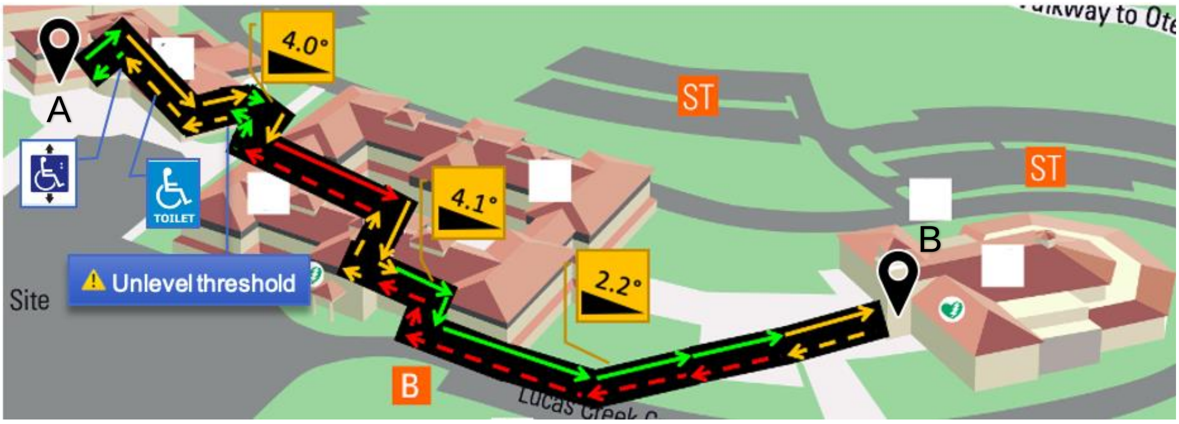
Directions from A to B	Energy Cost	Directions from B to A	Energy Cost
Head towards the student central Floor material: Exposed aggregate concrete Slope: Level	366 J	**Exit Atrium Building and head towards the curved slope** Floor material: Brickwork Slope: Level Doorway: Press button to open (960 mm wide) Threshold: 18 mm change in level	804 J
Go down the slope linking to the footbridge Floor material: Exposed aggregate concrete Slope: 2.1 degrees (downwards)	0 J	**Go up the curved slope** Floor material: Exposed aggregate concrete Slope: 3.4 degrees (upwards)	2973 J
Cross the footbridge to enter the student central Floor material: Exposed aggregate concrete Slope: 1.6 degrees (upwards) Doorway: Automatic sliding door (1200 mm wide)	1002 J	**Go up the slope in the student central plaza** Floor materials: Outdoor stone tiles Slope: 2.2 degrees (upwards)	1971 J
Take the accessible lift from L2 to L1 Floor material: Indoor smooth concrete Slope: Level Doorway: Lift door (1100 mm wide)	522 J	**Head towards the student central and enter the building** Floor material: Outdoor stone tile Slope: Level Doorway: Automatic sliding door (2400 mm wide)	584 J
Leave the building Floor material: Indoor smooth concrete Slope: Level Doorway: Automatic sliding door (2400 mm wide)	191 J	**Take the accessible lift from L1 to L2** Floor material: Indoor smooth concrete Slope: Level	191 J
Turn right towards the student central plaza Floor material: Outdoor stone tile Slope: Level	584 J	**Exit the student central** Floor material: Indoor smooth concrete Slope: Level Doorway: Automatic sliding door (1200 mm wide)	522 J
Go down the slope Floor materials: Outdoor stone tiles Slope: 2.2 degrees (downwards)	0 J	**Cross the footbridge** Floor material: Exposed aggregate concrete Slope: 1.6 degrees (downwards)	0 J

Go further down via the curved slope Floor material: Exposed aggregate concrete Slope: 3.4 degrees (downwards)	0 J	**Go up the slope** Floor material: Exposed aggregate concrete Slope: 2.1 degrees (upwards)	1073 J
Turn left and entry the Atrium Building via the accessible entrance on the left hand side Floor material: Brickwork Slope: Level Doorway: Press button to open (960 mm wide) Threshold: 18 mm change in level	804 J	**Head towards the Pukeko Hall** Floor material: Exposed aggregate concrete Slope: Level	366 J
Total energy cost	3469 J	**Total energy cost**	8484 J

Table 9: Navigation plans for Route 1.

Route 2 (252.1m, 34% indoor, 66% outdoor)

Point A: Atrium Building teaching room AT1
Point B: Main entrance of Massey Business School (MBS)

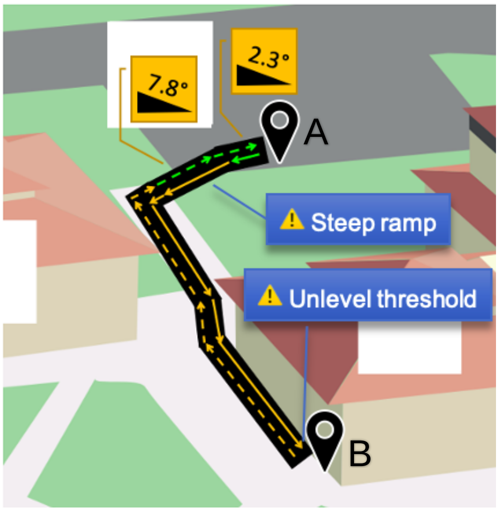


Directions from A to B	Energy Cost	Directions from B to A	Energy Cost
From the door of AT1, turn left and take the accessible lift from level 1 to level L1 Floor material: Indoor smooth tiles Slope: Level	165 J	**Head towards the sloped accessible path** Floor material: Brickwork Slope: Level	714 J
Turn right and go through the corridor Floor material: Indoor carpet Slope: Level Doorway: Press button to open (970 mm wide)	940 J	**Go up the slope and turn right towards the accessible ramp** Floor material: Brickwork Slope: 2.2 degrees (downwards)	2971 J
Leave the building and turn around to the accessible ramp Floor material: Brickwork Slope: Level Doorway: Press button to open (1920 mm wide) Threshold: 30mm change in level	176 J	**Go up the accessible ramp** Floor material: Brickwork Slope: 4.1 degrees (downwards)	2400 J
Go up the accessible ramp Floor material: Brickwork Slope: 4.0 degrees (upwards)	973 J	**Go to the opposite side of the Quad A via the lobby** Floor material: Indoor smooth tiles Slope: Level Doorway: Automatic sliding door (2320 mm wide)	687 J
Turn left and head towards the Quad A building Floor material: Brickwork Slope: Level	1300 J	**Turn left and head towards the Atrium Building** Floor material: Brickwork Slope: Level	1300 J
Go to the opposite side of the Quad A via the lobby Floor material: Indoor smooth tiles Slope: Level Doorway: Automatic sliding door (2320 mm wide)	687 J	**Go down the accessible ramp towards the Atrium Building** Floor material: Brickwork Slope: 4.0 degrees (downwards)	0 J
Turn left and go down the accessible ramp Floor material: Brickwork Slope: 4.1 degrees (downwards)	0 J	**Enter the Atrium Building** Floor material: Brickwork Slope: 0 Doorway: Press button to open (1920 mm wide) Threshold: 30mm	176 J

Turn left at the bollards Floor material: Brickwork Slope: 2.2 degrees (downwards)	0 J	**Go through the corridor and take the accessible lift from level L1 to level 1** Floor material: Indoor carpet Slope: flat Doorway: Press button to open (970 mm wide)	940 J
Head towards the MBS Floor material: Brickwork Slope: Level Doorway: Automatic sliding door (2280 mm wide)	714 J	**Turn right and head towards AT1** Floor material: Indoor smooth tiles Slope: Level	165 J
Total energy cost	4955 J	**Total energy cost**	9353 J

Table 10: Navigation plans for Route 2.

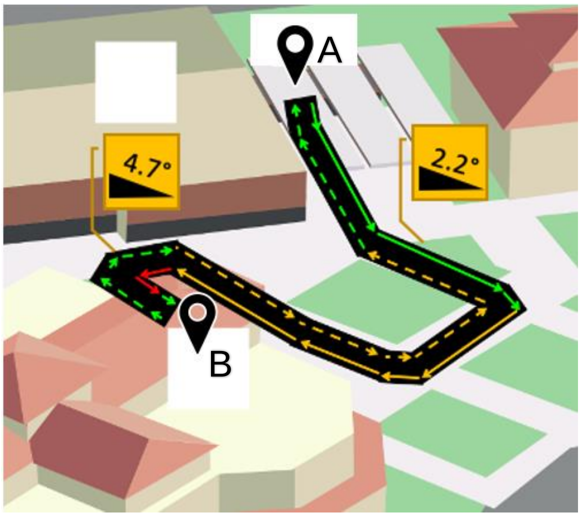
Route 3 (52.9m, 100% outdoor)
Point A: Mobility carpark near the library
Point B: Side entrance of the library



Directions from A to B	Energy Cost	Directions from B to A	Energy Cost
Head towards the campus and the concrete ramp Floor material: Asphalt Slope: 2.3 degrees (upwards)	267 J	**Turn right and head towards the carpark** Floor material: Exposed aggregate concrete Slope: Level Doorway: Opened door (2100 mm wide) Threshold: 25 mm change in level	929 J
Go up the ramp Floor material: Exposed aggregate concrete Slope: 7.8 degrees (upwards)	977 J	**Go down the ramp** Floor material: Exposed aggregate concrete Slope: 7.8 degrees (downwards)	0 J
Turn left and head towards the entrance of the library Floor material: Exposed aggregate concrete Slope: Level Doorway: Opened door (2100 mm wide) Threshold: 25 mm change in level	929 J	**Head towards the carpark** Floor material: Asphalt Slope: 2.3 degrees (downwards)	0 J
Total energy cost	2173 J	**Total energy cost**	929 J

Table 11: Navigation plans for Route 3.

Route 4 (120.7m, 100% outdoor)			
Point A: Main entrance of the café Point B: Main entrance of the SNW lecture theatre			

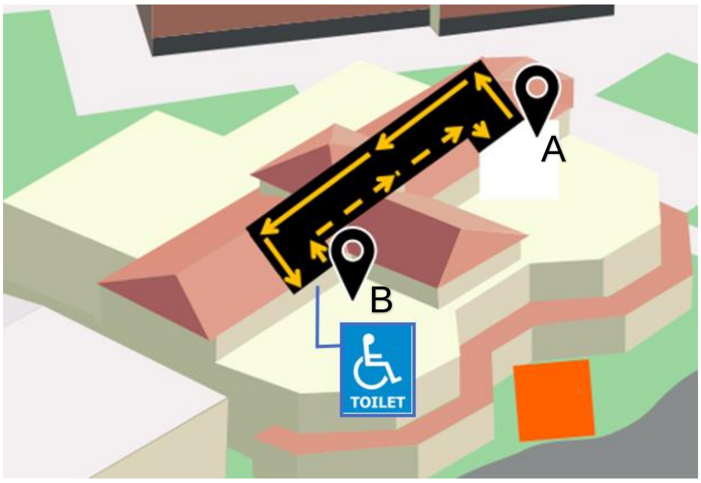


Directions from A to B	Energy Cost	Directions from B to A	Energy Cost
Head towards the slope in student central plaza Floor material: Outdoor stone tiles Slope: Level	636 J	**Turn left towards the accessible ramp** Floor material: Outdoor stone tile Slope: Level Doorway: Press button to open (1760 mm wide)	206 J
Go halfway down the slope Floor material: Outdoor stone tiles Slope: 2.2 degrees (downwards)	0 J	**Go down the accessible ramp** Floor material: Exposed aggregate concrete Slope: 4.8 degrees (downwards)	0 J
Turn right and head towards to accessible ramp outside the SNW Theatre Floor material: Outdoor stone tiles Slope: Level	911 J	**Head towards the slope in student central plaza** Floor material: Outdoor stone tiles Slope: Level	911 J
Go up the accessible ramp Floor material: Exposed aggregate concrete Slope: 4.8 degrees (upwards)	2337 J	**Go up the slope** Floor material: Outdoor stone tiles Slope: 2.2 degrees (upwards)	821 J
Enter the SNW Theatre Floor material: Outdoor stone tile Slope: Level Doorway: Press button to open (1760 mm wide)	206 J	**Head towards the café** Floor material: Outdoor stone tiles Slope: Level	636 J
Total energy cost	4090 J	**Total energy cost**	2574 J

Table 12: Navigation plans for Route 4.

Route 5 (30.4m, 100% indoor)

Point A: Lecture room SNW200
Point B: Accessible toilet in SNW lecture theatre

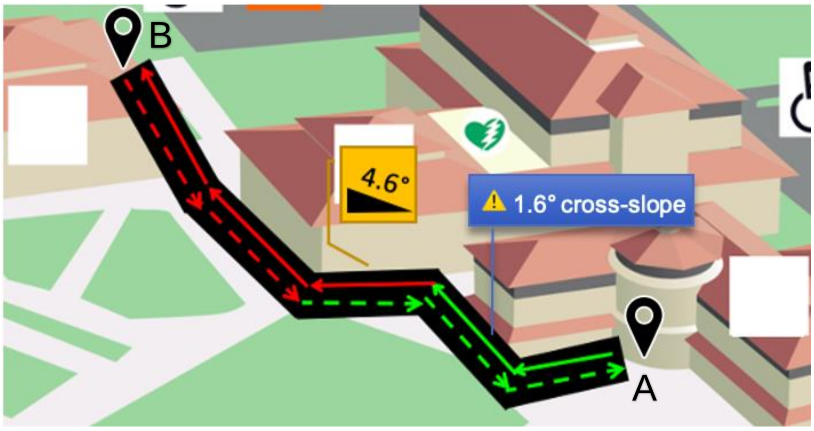


Directions from A to B	Energy Cost	Directions from B to A	Energy Cost
Turn left and head towards the accessible toilet on the same floor Floor material: Indoor carpet Slope: Level Doorway: Pull manually (860 mm wide)	744 J	**Turn right and head towards the SNW200** Floor material: Indoor carpet Slope: Level Doorway: Pull manually (860 mm wide	744 J
Total energy cost	744 J	**Total energy cost**	744 J

Table 13: Navigation plans for Route 5.

Route 7 (108.5m, 100% outdoor)

Point A: Main entrance of Atrium Building
Point B: Main entrance of Mathematics Sciences Building



Directions from A to B	Energy Cost	Directions from B to A	Energy Cost
Turn right and head towards the accessible ramp outside the library Floor material: Brickwork Slope: Level Cross-slope: 1.6 degrees	680 J	**Turn right and head towards the accessible ramp outside the library** Floor material: Exposed aggregate concrete Slope: Level Doorway: Automatic sliding door (1100 mm wide)	1014 J
Go up the zig-zag accessible ramp Floor material: Exposed aggregate concrete Slope: 4.6 degrees (upwards)	3096 J	**Go down the zig-zag accessible ramp** Floor material: Exposed aggregate concrete Slope: 4.6 degrees (downwards)	0 J
Turn right and head towards the Mathematical Sciences Building Floor material: Exposed aggregate concrete Slope: Level Doorway: Automatic sliding door (1100 mm wide)	1014 J	**Head towards the Atrium Building** Floor material: Brickwork Slope: Level Cross-slope: 1.6 degrees	680 J
Total energy cost	4790 J	**Total energy cost**	1694 J

Table 14: Navigation plans for Route 7.

5. DISCUSSION

5.1 Findings

5.1.1 Accuracy of the experimental method

This research used the experimental method of measuring the rolling resistance for pulling a loaded MWC on the paths. As discussed in Section 4.2, the results from the accuracy tests and the statistical analysis showed that the method is highly repeatable with consistent measurement. Also, the influence of weight on the rolling resistance is assessed by analyzing the difference in the rolling resistance of the 5 weights (55, 60, 65, 70 and 75 kg load on the MWC) on the same path (refer to Table 7). The results showed that the rolling resistance increased as the load increased on both the indoor and the outdoor paths, which is supported by the equations provided in Section 3.3. Using the values of rolling resistance to calculate the coefficient of rolling resistance (C_{rr}), the C_{rr} of the outdoor path with a rougher surface is higher than the C_{rr} of the indoor path. Therefore, this experimental method is statistically reliable for measuring the rolling resistance on different surfaces and is valid for a range of MWC users' weights.

Applying the experimental method on the sample routes, for indoor paths, it is shown in the results that the rolling resistance was higher on carpet (24.5 N on segment 5.1) than on smooth concrete (18.2 N on segment 1.4), which aligns with the previous studies that explained this as a result of the deformation of energy on softer surfaces (Chan et al., 2018; Sauret et al., 2012). For outdoor paths, comparing the level paths on different surface materials, the rolling resistance was higher on brickwork (33.0 N on segment 1.9) than on stone tiles (18.0 N on segment 1.6). Although both outdoor paths were on hard surfaces, the condition of the brickwork path is poorer with cracks and uneven brick pavement (see Figure 10), which could be the reason of the higher rolling resistance for overcoming surface irregularities (Hurd et al., 2008). These demonstrate that the experimental method reflected the energy required for propelling a MWC on different surfaces in the sample routes.

Figure 10: Surface condition of a brickwork path.

The influence of slopes on the rolling resistance was also reflected during the data collection on the sample routes. For each type of surface materials, the rolling resistance on sloped surfaces is higher than the level surfaces (refer to Figure 5). This influence on the rolling resistance (which was the spring balance reading during the experiment) can be measured by using the Equation (3) in Section 3.3, which includes the gravitational force component. For example, both segments 7.2 (with a 4.6 degree slope) and 7.3 (level surface) are exposed aggregate concrete paths but the average rolling resistance for the sloped and level segments are 85.2 N and 23.9 N respectively. By putting the value of rolling resistance and the slope angle in the equation, the drag force parallel to the surface for segment 7.2 is:

$$F_{roll} = 85.2 - 77.55(9.81)(\sin 4.6°) = 24.2\ N \quad (6)$$

where F_{roll} is the drag force parallel to the sloped surface, 77.55 kg is the total weight of the load and the MWC and 9.81 ms^{-2} is the gravitational acceleration.

For segment 7.3 (a level surface with the same surface material), the drag force is the rolling resistance measured in the experiment (i.e. 23.9 N), which is close to the value of F_{roll} for segment 7.2. This demonstrates that the method covers the forces on slopes in the measurement. In summary, the experimental method is reliable for assessing the influence of the (i) weight, (ii) surface roughness and (iii) slope of the accessible paths on the rolling resistance and the energy required for using these paths.

5.1.2 Main factors of energy cost

In the case study of the Massey University East Precinct Campus, the buildings are situated at different altitudes and connected by the accessible routes. These routes inevitably involve transitions between different levels for the users to navigate around the campus. For instance, the Massey Business School is located at a lower level of the campus (see Figure 11). Most people usually use the stairs to transit to another level of the campus efficiently, while MWC users need to use the slope or the accessible ramp to move around the stair and transit between different levels.

Figure 11: A photo taken from the Massey Business School.

A main factor of the energy cost is the travel direction of the route. By considering the energy cost of the sample route in both travel directions (refer to Figure 9), it is shown that even on the same path, the required physical effort can vary due to the travel direction when there are sloped surfaces in the route. For instance, in Route 1 where the student accommodation (Point A) is located at a higher level than the Atrium Building (Point B) and the route is mostly going downhill when going from Point A to Point B. It is reflected by the energy cost that going from point A to point B requires 3467.9 J to propel a MWC, while the opposite direction (mostly uphill) requires 8482.1 J. The results showed that when MWC users navigate in the built environment, they would spend a lot more physical effort when going from a lower level to a higher level. Reversely, the energy cost is assumed to be 0 J when the MWC users can free-wheel down the slope and this would save their energy by coasting down in the wheelchair.

On the other hand, it would also be harder for MWC users to propel on steeper slopes in the accessible routes. In the segment 3.2 of the sample routes, the angle of the slope is 7.8 degrees which exceeds the maximum allowable gradient set in the NZBC compliance standards. The average rolling resistance for that segment was measured as 124.9 N (refer to Figure 5). In comparison, the average force for an allowable accessible ramp with an angle of 4.6 degrees (segment 7.2) was measured as 85.2 N. The results showed that when the slope is steeper, it is harder for the MWC users to drive up it as the required force is higher. This aligns with the previous studies which found the muscles activity and shoulder joint impacts increased as the slope angle increased or as the propulsion task got more challenging (Holloway et al., 2015).

When going uphill, the MWC tends to run backwards between strokes and the MWC users need to shorten their recovery phase in each stroke to catch the pushrims and prevent the MWC from running backwards, which becomes a massive effort for the MWC users to propel up the slope (especially on ramps that are too steep). Therefore, the design for the built environment should take the landscape into consideration. When travelling between different levels cannot be avoided in the built environment, the slope and the accessible ramp need to be strictly controlled according to the accessibility standards. In some cases, an accessible lift would be an efficient option to allow the MWC users to move between levels without exhausting themselves from propelling in hard situations.

5.1.3 Compliance with the accessibility standards

After measuring the physical features in the sample routes on the campus, it was found that some parts of the routes can be improved or rectified to meet accessibility standards for the built environment. As discussed in Section 2.1, the NZS4121:2001 provides the standards for a route in the built environment to be accessible for wheelchairs and comply with the NZBC clause D1 – Access routes. It covers the requirements in accessible routes such as slope, cross slope and doorways. Although most of the sample routes is complied with the standards, some parts failed to fulfil these requirements based on the on-site measurement. The non-compliant features are also marked in the navigation plans as these can pose particular challenges for MWC propulsion.

(i) Gradient of ramp

In the NZS4121:2001, the section 6 provides the requirement for a ramp to be accessible. It is suggested that every effort should be made to construct a ramp as flat as possible and provided that the maximum gradient for an accessible ramp is 1:12 (i.e. 4.76 degrees). Based on the on-site measurement, the ramp connected to the mobility carpark near the library in Route 3 (segment 3.2) has a slope of 7.8 degrees which exceeds the maximum allowable angle set in the standard (see Figure 12). Also, the NZS4121:2001 requires the surface of the mobility carpark to be level (i.e. flatter than 1.15 degrees). However, the slope of the parking lot in the sample route is 2.3 degrees, which exceeds the maximum allowable slope for a carpark. Although the mobility carpark is located proximately to the library, it would still be physically demanding for the MWC users to use this route via the non-compliant features (especially on the steep ramp which could be unusable to some MWC users as the required push force is too high). This area should be improved by flattening the surfaces to allow MWC users to come from the same carpark with a lower maximum energy cost.

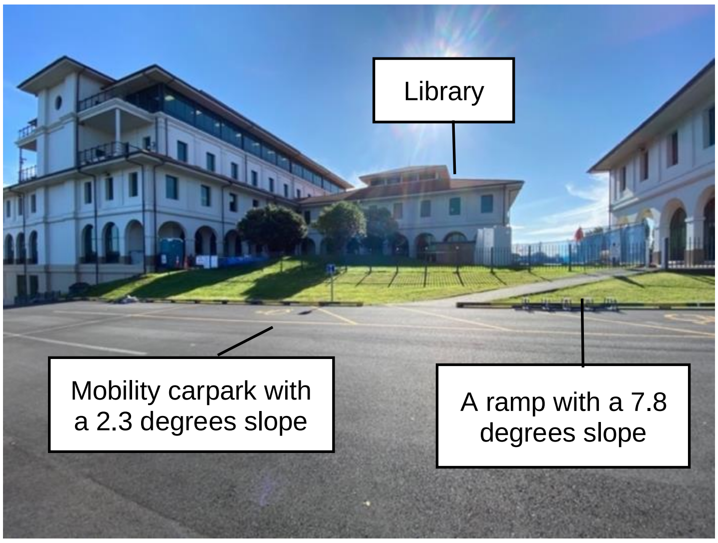


Figure 12: The mobility carpark near the library.

(ii) Shape of ramp

According to the NZS4121:2001, a footpath with a gradient steeper than 1:20 (i.e. 2.86 degrees) should be treated as a ramp. A slope in the Route 1 (segment 1.8) falls under this requirement as a 'footpath as ramp' with a gradient of 3.4 degrees (See Figure 13). However, since it is a curved sloped, it should not be considered as an appropriate accessible path according to the section 6.4.1 in NZS4121:2001. Although it is not reflected in the experimental results, a MWC user is expected to spend more energy to compensate for the resistive forces (other than the rolling resistance) when propelling on a curved path. These resistive forces include the scrub torque for turning the wheelchair and the uneven forces in the arms due to the bilateral asymmetry (Lin et al., 2015; Stephens & Engsberg, 2010). In the case of this segment, the MWC users may use an alternative accessible ramp to transit between the two levels to avoid the difficulty of using a curved path. However, a sign should be added near the curved ramp to alert the MWC users and direct them to the alternative route.

Figure 13: A curved ramp near the Atrium Building.

(iii) Cross-slope

The cross-slope is the transverse slope on a path which is perpendicular to the wheelchair travel direction. The casters of the wheelchair tend to turn to the lower side when moving on a path with cross-slope, which can also affect the rolling resistance. MWC users would need to balance themselves by pushing harder in the arm on the lower side to keep the wheelchair going straight forward, which can be tiring and damaging to the joints in that arm (Holloway & Tyler, 2013). In the NZS4121:2001, the maximum allowable cross-slope gradient is 1:50 (i.e. 1.15 degrees). Most parts of the sample routes have a small cross-slope with an angle smaller than 1, except for one part in the Route 7 (segment 7.1) which has a cross-slope of 1.6 degrees. However, a cross-slope is also used to provide drainage of rainwater and cannot be removed entirely from the built environment. But it should be kept within the allowable gradient provided in the accessibility standard, especially on ramps or sloped paths because it is hugely challenging for MWC users to handle both types of slope at the same time.

(iv) Unlevel threshold

The threshold at the building entrance should be level or designed according to the NZS4121:2001. The standard provides that contrasted strips should be arranged for thresholds less than 20 mm, while a ramp is required for thresholds greater than 20 mm. However, some of the thresholds in the sample routes have not fulfilled these requirements such as a threshold of 30 mm without a ramp or a lower threshold without contrasted strips. In particular, the threshold at the entrance of the library has two changes in level (see Figure 14) since the entrance is moved to the current location due to a temporary work at the original entrance. When MWC users come across these thresholds, they may use the suitable wheelchair skills to transit in or out of the building safely. The energy cost for these skills is not measured in this research since it has a small effect to the rolling resistance and the transition is relatively small to the overall energy cost for the whole routes. But this should still be rectified on the campus to provide a fully accessible built environment.

Figure 14: Threshold at the library entrance.

5.2 Limitations

5.2.1 Blocked path

Although the experiment could measure the rolling resistance to determine the energy cost of using the routes, it could only be carried out on the paths that are physically accessible to the wheelchair. During the data collection of this research, part of a sample route (Route 6) was blocked for the temporary work and became inaccessible for all pedestrians. There were signs suggesting using an alternative route nearby to bypass the work site. However, the suggested alternative route was impassable to wheelchairs as it involved steps and narrow width (see Figure 15). Without this part of the route to maintain the overall connectivity of the route, the whole route became unusable for MWC users. Hence, the experiment could not be conducted in this route due to the limitation of this method.

In this kind of situation where the route is inaccessible for wheelchairs due to temporary obstacle, MWC users will have to rely on the updated information from the relevant organization (in this case the university) and its disability service to plan their journey accordingly. If a MWC user only realizes the blocked path and the nearby alternative path are inaccessible when they are already close, it can be hard or even impossible for them to find another route to the destination. Therefore, the information of the energy cost in the navigation plans is not comprehensive enough for the actual use for MWC users, it has to be supported by the updated information of the temporary obstacles and valid alternative routes.

Figure 15: An inaccessible alternative path.

5.2.2 Movement of the MWC user

Another limitation of the experimental method is that the pulling motion could not fully replicate the movement of a MWC user during wheelchair propulsion. When MWC users propel through the built environment, they may use different techniques or body postures when approaching different types of propulsion tasks. For instance, when propelling a MWC on a path with a cross-slope (where the casters tend to turn sideways towards the downslope), the MWC user has to push harder on the lower side to balance the wheelchair and keep driving straight. Additionally, when driving up an inclined surface, the MWC users tend to lean forward to shift their centre of gravity and use a push pattern with a shorter recovery to avoid rolling backwards between the strokes (Qi et al., 2013). These movements can influence the rolling resistance as the weight distribution loading on the casters and the rear wheels changes (Sauret et al., 2012).

In the experiment, pulling the MWC from the mid-point of the tie-downs constrained the wheelchair movement to follow the travel direction constantly. Although this would provide a stable measurement of the rolling resistance, it may not fully reflect the biomechanics of the propulsion stroke such as the shoulder joint forces and muscles demand (Sprigle & Huang, 2015). However, the rolling resistance is a consistent and objective factor that primarily influences the wheelchair propulsion effort. When corresponding the computed energy cost to the perceived effort, MWC users can compare it to their individual capability by trial-and-error and develop their own set of interpretation to the information.

5.3 Future recommendation

5.3.1 Digitalizing the navigation plans

Since this research used a new protocol for accessibility mapping by dominantly using the computed energy cost, it needs to be further improved for the navigation system to be actually usable. In this research, the navigation plans and the map for each route were produced individually based on the experimental results. This process is unavoidably time-consuming and inflexible for changes of information. In order to utilize the obtained data, the data can be integrated into a digitalized navigation system that allows more flexible editing. For instance, the temporary features or obstacles can be edited on a digitalized system and updated from time to time to reflect the current situation of the path. This can provide more accurate and useful information for the MWC users.

Moreover, alongside the basic navigation information that most people need, MWC users need some extra path information specifically for wheelchair navigation. The extra information may include energy cost, physical features in the routes and photos of these features. It could be overwhelming to put all the details of the route on one page, especially when it is on the screen of a mobile phone. If the system is digitalized, the users can filter the information to what they need personally by opening and closing the appropriate information. They can then read the map and the directions more efficiently.

5.3.2 Expanding the coverage

This research has covered the sample routes that were selected based on the usually visited places on the campus. The coverage of the data can be expanded to connect and integrate into the existing data. Taking this case study as an example, the scale of the map can be expanded to cover the whole Massey University East Precinct campus. When there is sufficient data, all accessible routes in the area can be inter-linked consistently. The system can then generate different routes for the same pair of origin and destination if alternative routes are available. This can allow the users to compare different routes and choose the preferable one by evaluating the condition and the required energy cost of the routes.

Another benefit of a larger database is that it can provide more accurate cut-off values for colour coding the accessibility level in the map so that the levels can be more precise. However, the 3 colours used on the map (red, yellow and green) is not necessarily the ideal colour scheme to use for people who are red-green colour blind. It would be fitter for the MWC users to judge if they can correspond their capability to the energy cost with the concept of the capability model (i.e. provided capabilities vs required capabilities) by comparing the energy output they can provide and the energy required for using the paths (Tyler, 2011). Depending on individual capabilities, MWC users can judge whether the path is easy or hard. Since the data in the navigation system reflect the required energy objectively and consistently, it can be used by MWC users with varied conditions (such as different physical impairment, wheelchair type and weight distribution between the casters and rear wheels). By measuring more paths, more data can be provided for MWC users as reference to determine the energy levels correctly.

6. CONCLUSION

The accessibility of the built environment can hugely impact the navigation of MWC users. Having reliable information about the routes can provide confidence for the MWC users before their trips and reduce the chance of approaching an inaccessible path. Previous studies have calculated the wheelchair accessibility by asking the MWC users to rank the difficulty of using the paths, which relied on the subjective, individual feedback. Other researchers have measured the required force for pre-arranged propelling tasks in laboratory setting. This research has developed an accessibility assessment on real paths that a MWC user would use by evaluating the path objectively.

Rolling resistance is the primary cause of energy loss in MWC propulsion and is highly related to the perceived effort of the MWC users. It was measured in the research experiment to generate consistent data for reflecting the reaction force of pulling a MWC along the sample routes. The data were then used to compute the energy cost of using the routes. The results showed that the energy cost depends heavily on the difference in the altitude of the locations and whether the MWC user is travelling uphill or downhill. Obviously, it is harder for a MWC user to propel themselves up a sloped surface than to free-wheel down it. It is even more challenging when the path is rough and the slope is steeper, curved or has a cross-slope allowing for water drainage.

The energy cost of each route was computed and colour-coded on the map to show the required physical effort for using each route in both directions. Features that failed to meet statutory compliance such as ramp slopes and cross-slopes are shown on the map since they present physical challenges which may be insuperable to MWC users. Furthermore, the facilitators in a built environment such as accessible toilets and accessible lifts were marked on the map. Alongside the map, the navigation plans contain directions showing relative ease and detailed description of different parts of the routes. This is similar to the Google Maps directions that facilitate driving from one place to another. Although this is presented in document format in this work, in future work it could be extended to an App for a smart phone.

One limitation of this research is that the energy cost may not fully represent the biomechanics of the MWC propulsion. MWC users may apply different skills or push patterns as they approach different propelling tasks in the built environment, which are not included in the computed energy cost. However, the rolling resistance is the major source of energy cost in MWC propulsion and its measurement is independent to these factors as a true representation of the required energy on each path. Each individual MWC user can determine their capability (energy output) by travelling along the measured paths and determining the energy level that they can handle. By comparison, the qualitative methods are subjective and what may be judged easy by one MWC user may not be possible for another more physically-challenged user. Future researches can follow the same experiment protocol in other areas to expand the coverage of the navigation. With more data on the energy cost for different types of environment, the MWC users can correspond the energy cost level according to their own preference and develop their own interpretation effectively.

The experimental method of measuring the rolling resistance of the loaded MWC in this research is determined to be consistent with a high repeatability as shown in the statistical variations of the measurement. The statistical tests showed that rolling resistance measured on the same path with the same set-up generated data with no statistical differences. By varying the weight, the rolling resistance increased with a statistical difference as the weight increased, which showed the method is valid for a range of MWC users' weights. When measuring different surfaces, it was shown that the rolling resistance is higher on rougher or sloped surfaces. In terms of energy cost, the required energy for MWC users to propel increases as either the rolling resistance or the distance increases. Therefore, this method can provide reliable input to the computation of energy cost of the routes as a specific navigation information for MWC users.

An important finding of this research was that it showed the need of having resilient accessible path for MWC users. With a portion of the accessible route being blocked, the sign directed the users to an alternative path with stairs, which was inaccessible to MWC users. Although it is a small minority on the campus, it seems unkind to place unnecessary barriers in their way. Finally, the findings can also be used to encourage the principles of universal design in the built environment. For example, as Massey University Facilities Management try to improve MWC accessibility on the campus, they can focus their efforts on remedying the features that are non-compliant with the NZBC clause D1 Access Route (such as flattening the steep ramp). By removing these barriers to MWC in the built environment, the MWC user accessibility can be improved to allow them to navigate between the places to participate in various activities more easily.

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APPENDICES

Appendix 1 – Background information on disabilities of MWC users

Disability as a dynamic interaction between a person and the environment

Many individuals have to rely on manual wheelchairs (MWCs) after suffering from diseases or injuries, such as spinal cord injuries. Using a MWC is not necessarily regarded as disability because disability is a result of the influence of various factors in their lives. The International Classification of Functioning, Disability and Health (ICF) is a well-known framework that describes health and health-related issues (World Health Organization, 2001). The model of ICF components recognizes that environmental factors and structures can affect body function, activities and participation, which all together interact dynamically with the overall condition of a person's health. In other words, environmental factors may restrict or facilitate an individual's performance depending on the number of physical facilitators or barriers in the environment. For example, a building without an accessible bathroom or elevator creates barriers for the wheelchair users to their participation in the society and in contrast, an accessible design may improve health conditions.

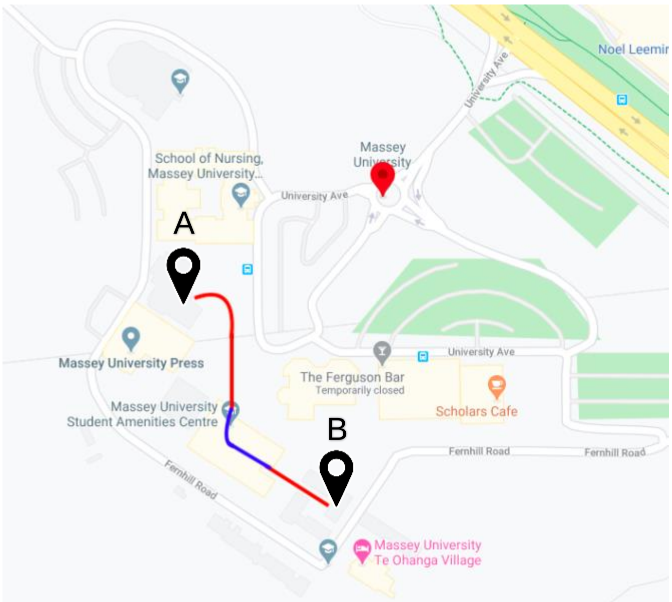
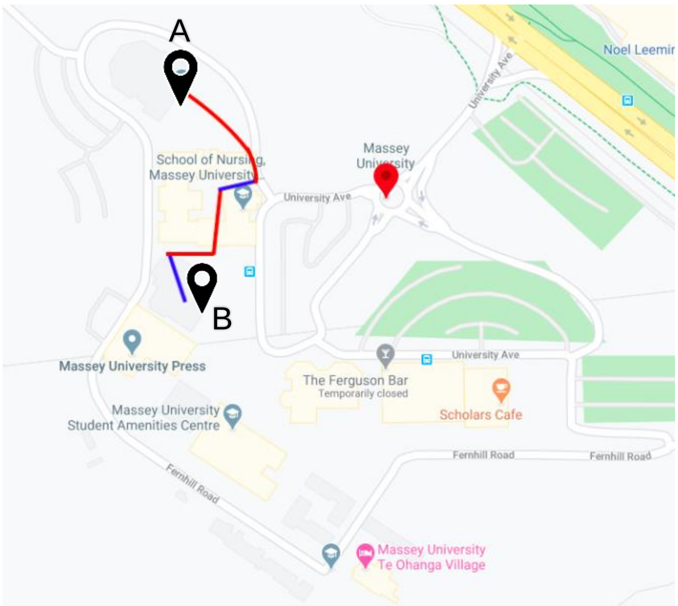
Improving the environment to reduce disability

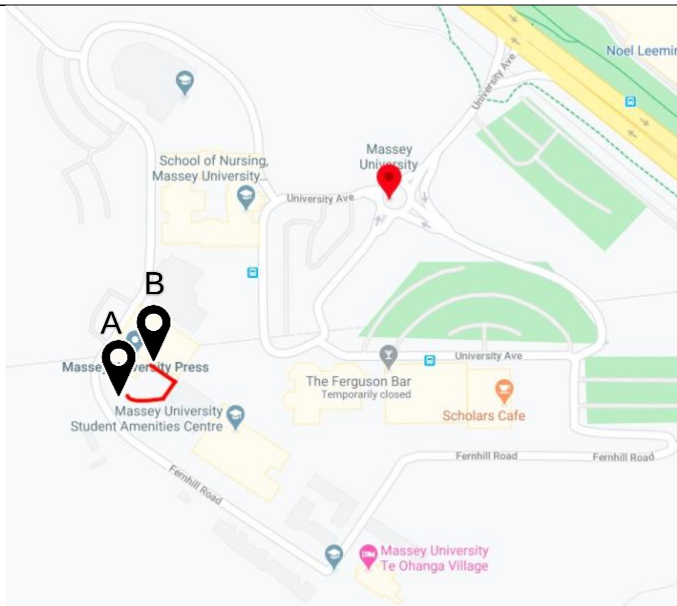
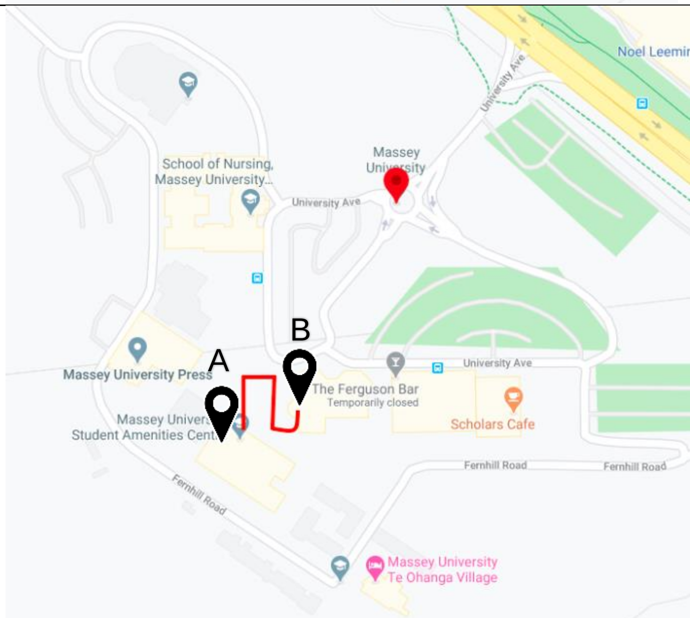
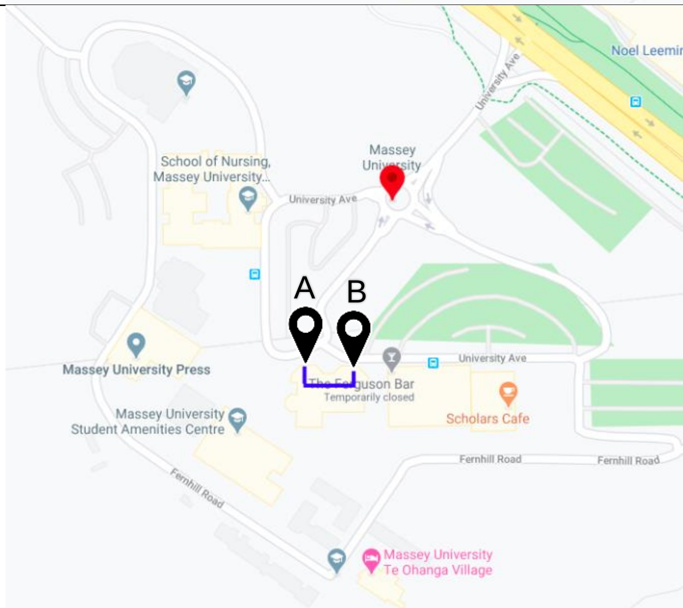
According to the World Health Organization (2011), the extent of disability can be assessed by measuring the influence of the environment on a person's (i) capacity: what a person can do in a standardized environment without the barriers and facilitators and (ii) performance: what a person does in an usual environment with all barriers and facilitators. In order to maximize a person's performance with the given capacity (taken into account their impairment), an 'enabling environment' has to be created from several aspects to address the inaccessibility and barriers in the public accommodation. These aspects include (i) developing effective policies, (ii) improving standards, (iii) enforcing laws and regulations, (iv) the lead agency, (v) monitoring, (vi) education and campaigning and (vii) adopting universal design.

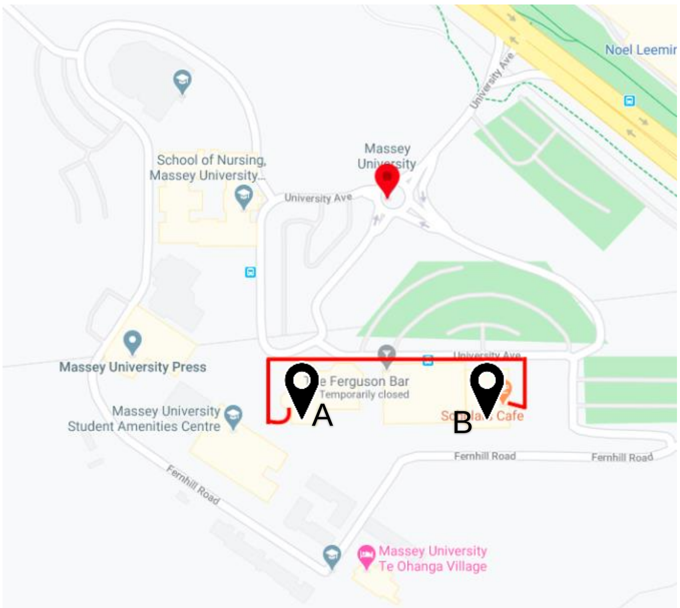
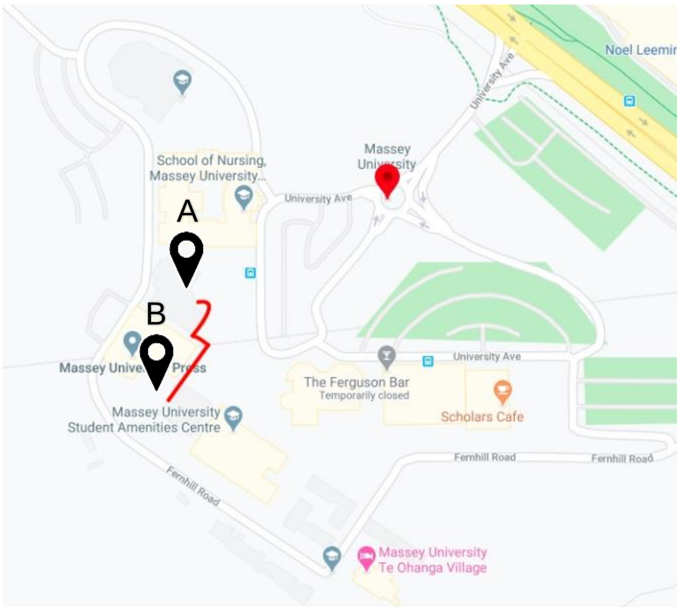
Principles of universal design

Universal design is defined as "a process that enables and empowers a diverse population by improving human performance, health and wellness and social participation" (Steinfeld & Maisel, 2012, p. 29). It can be interpreted as a concept that emphasizes a user-centred approach to design and provide environments or products to be usable for people of all sizes, ages and abilities. The concept includes providing a built environment that is equally accessible, usable and understandable for everyone at little or no extra cost (Null, 2013, p. 4). There are seven basic principles of universal design, namely, (i) equitable use, (ii) flexibility in use, (iii) simple and intuitive use, (iv) perceptible information, (v) tolerance for error, (vi) low physical effort and (vii) size and space for approach and use (The Center for Universal Design, 1997).

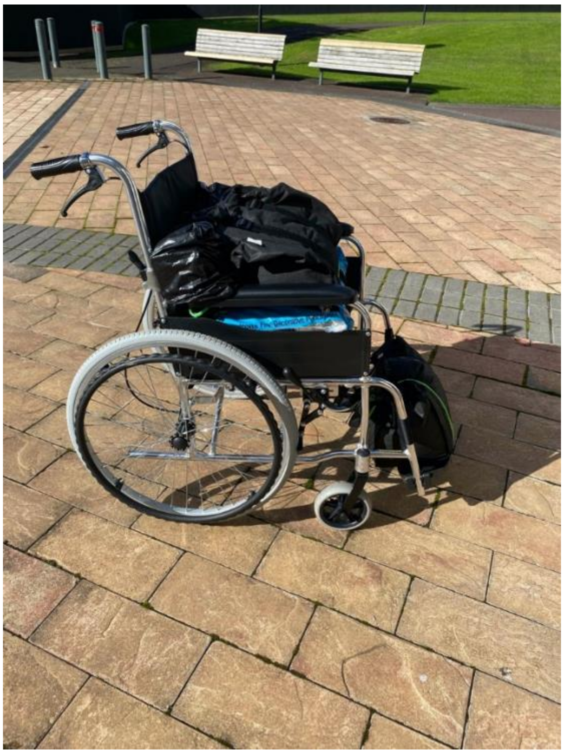
Appendix 2 – Locations of the sample routes

Route details	Locations of route on map (Google Maps, n.d.) *(Red line = outdoor path; Blue line = indoor path)*
<u>Route 1</u> Point A: Entrance of Pukeko Hall (student accommodation) Point B: Main entrance of Atrium Building Places in between: Student Central Student Central Plaza	
<u>Route 2</u> Point A: Atrium Building teaching room AT1 Point B: Main entrance of Massey Business School Places in between: Staff office Campus information services	

<u>Route 3</u> Point A: Mobility carpark near the library Point B: Entrance of the Library	
<u>Route 4</u> Point A: Café main entrance door Point B: Entrance of SNW lecture theatre Places in between: Student Central Plaza	
<u>Route 5</u> Point A: SNW200 lecture room Point B: Accessible toilet in SNW	

<u>Route 6</u> Point A: Entrance of SNW lecture theatre Point B: Entrance of Recreation Centre Places in between: Student Central Plaza Public bus stop Car pick-up point Carpark (Part of this route is blocked during data collection due to a temporary work site.)	
<u>Route 7</u> Point A: Main entrance of Atrium Building Point B: Entrance of Mathematical Sciences Building	

Appendix 3 – Details of the manual wheelchair used in the experiment

Details of the manual wheelchair used in the experiment	
Brand	Anko
Frame	Aluminium frame
Dimensions	Height: 91 cm (floor to handles) Width: 66 cm (rear wheel to rear wheel) Depth: 108 cm (rear wheel to footrests)
Weight	12.55 kg
Casters diameter	45 mm
Rear wheel diameter	540 mm
Photo	 (loaded with stones as described in Section 3)

Appendix 4 – Sensitivity of the measurement to tie-downs positions.

During the experiment, the tie downs are expected to move up and down slightly due to the hand movement when pulling the wheelchair. Bascou et al. (2013) suggested that the errors due to small misalignments of travel direction in the horizontal plane could be negligible but those in the sagittal plane should be corrected according to the gravitational force. In this research, the misalignment in the horizontal plane is minimized by fixing the spring balance at the centre point of the tie down for the errors to be negligible. Concurrently, the sagittal movement was maintained within ± 5 degrees from the horizontal direction for accurate results.

With the ± 5 degrees sagittal movement, the spring balance readings would not show the exact value of the rolling resistance (i.e. horizontal force for pulling the wheelchair) as the pulling force is not perfectly horizontal in the travel direction. The range of possible errors can be influenced by changing the position of the anchor point of the tie down straps. An example is shown in Figure 16 to illustrate the tie downs anchored at the seat level. In this example, F_{h1} is the pulling force as recorded in the spring balance, while F_H is the horizontal component of the pulling force (i.e. the rolling resistance). When the tie downs are elevated by 5 degrees (the maximum allowed angle), the rolling resistance is calculated as:

$$F_H = F_{h1}\cos(5) = 0.9962\ F_{h1} \qquad (7)$$

Equation (7) shows that the horizontal force component (F_H) will be around 0.004 smaller than the spring balance reading (F_{h1}), which means the spring balance reading is closely approximate to the rolling resistance (within 0.4%).

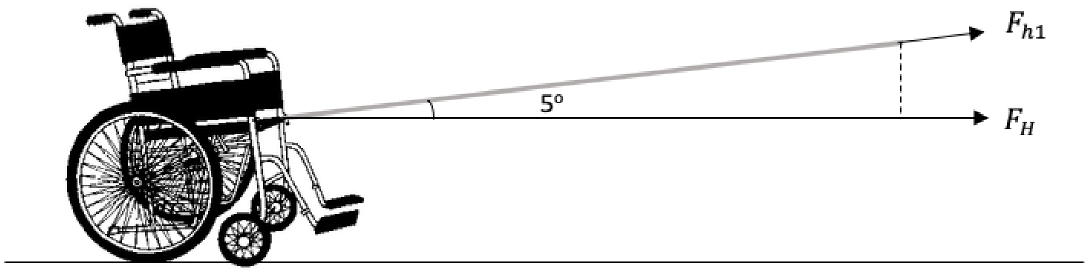


Figure 16: Horizontal forces of anchoring the tie downs at the seat level.

Another example is shown in Figure 17 to illustrate the tie downs anchored at the caster axle level. Since this level is much lower and closer to the ground, it is impractical to maintain the sagittal movement within 5 degrees. Assumed that the wheelchair is pulled with the spring balance 0.75m above the anchor point and the straps are 2m long, the angle between the tie downs and horizontal level is calculated as:

$$\theta = \sin^{-1}(\frac{0.75}{2}) = 22.02° \qquad (8)$$

Similar to Equation (7), the rolling resistance is calculated as:

$$F_H = F_{h2}\cos(22) = 0.9272\ F_{h2} \qquad (9)$$

where F_{h2} is the pulling force as recorded in the spring balance and F_H is the horizontal force component which is used to compute rolling resistance. Considering the hand movement of ± 5 degrees (i.e. from 17 degrees to 27 degrees), F_H can vary from 0.9563 F_{h2} to 0.8910 F_{h2}, ranging from 4.37% to 10.9% lower than the spring balance reading.

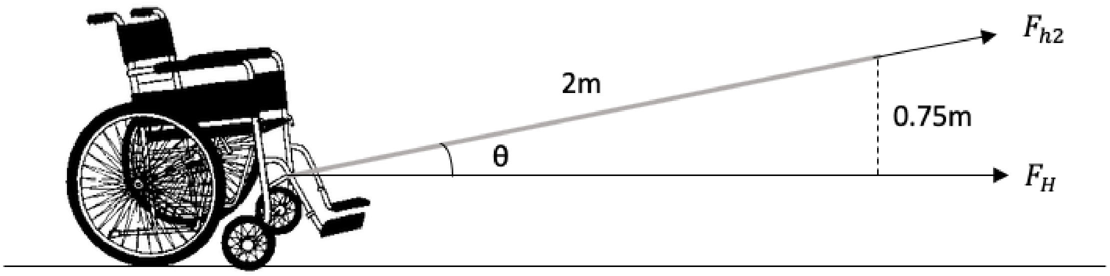


Figure 17: Horizontal forces of anchoring the tie downs at the caster axle level.

Based on the calculation, anchoring the tie downs at the seat level (rather than the caster axle level) can avoid significant errors and provide approximate value of rolling resistance from the spring balance readings. Hence, the tie downs were fixed on the wheelchair frame at just above the seat level for the set-up in the experiment. By controlling the sagittal alignment during the pulling movement, the experiment can operate within 5 degrees from the horizontal level to maintain the small difference between the pulling force and its horizontal component. When this difference is kept within 0.4% (as provided in the equations), the measurement of spring balance reading is directly used to compute the rolling resistance.

Appendix 5 – Statistical analysis of the accuracy test

In order to test the accuracy of the experimental method, the data from the accuracy test were analyzed using IBM SPSS Statistics for Windows, Version 26.0 (refer to Section 4.2). For the accuracy test with 65 kg load, Shapiro-Wilk test was used to check the normality of the data. The results for the 8 tests on each of the indoor and outdoor segments are shown in Figures 18 and 19 respectively (significant level = 95%). The null hypothesis was that the data are drawn from a normal distribution. A significant value greater than 0.05 indicates a normal distribution of data. In the results, the significant values are all greater than 0.05, which mean the data in each test is normally distributed.

ANOVA (analysis of variance) test was then used to check the statistical difference between the mean values of the repeated 8 tests (significant level = 95%). The null hypothesis was that there is no difference between the tests. A P-value smaller than 0.05 rejects the null hypothesis. In the results, the P-value for the indoor surface and the outdoor surface are 0.621 and 0.529 respectively (see Figure 20 and Figure 21), which are higher than 0.05 and indicate that there is no statistical difference among the data in the 8 tests on each of the indoor and outdoor surfaces.

In order to check the rolling resistance between different weights in the accuracy test, ANOVA test was used to check the mean values of the rolling resistance of the 5 measured weights on the indoor and outdoor segments (significance level = 95%). The null hypothesis was that there is no difference between the rolling resistance of different weights. A P-value smaller than 0.05 rejects the null hypothesis The P-value is 0.000 (see Figure 22), which is lower than 0.05 and indicates that the data from the 10 combinations (5 weights on each of the indoor and outdoor segments) are statistically different to each other.

Tests of Normality

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
IndoorTest1	.130	30	.200*	.944	30	.120
IndoorTest2	.071	30	.200*	.982	30	.875
IndoorTest3	.121	30	.200*	.950	30	.172
IndoorTest4	.097	30	.200*	.961	30	.321
IndoorTest5	.113	30	.200*	.982	30	.883
IndoorTest6	.114	30	.200*	.955	30	.234
IndoorTest7	.177	30	.017	.959	30	.294
IndoorTest8	.110	30	.200*	.958	30	.268

*. This is a lower bound of the true significance.

a. Lilliefors Significance Correction

Figure 18: Normality test results for accuracy test on the indoor surface (flat, smooth concrete).

Tests of Normality

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
OutdoorTest1	.145	30	.111	.971	30	.567
OutdoorTest2	.104	30	.200*	.948	30	.152
OutdoorTest3	.186	30	.009	.942	30	.104
OutdoorTest4	.103	30	.200*	.985	30	.942
OutdoorTest5	.096	30	.200*	.972	30	.600
OutdoorTest6	.175	30	.020	.948	30	.149
OutdoorTest7	.100	30	.200*	.956	30	.249
OutdoorTest8	.113	30	.200*	.981	30	.862

*. This is a lower bound of the true significance.

a. Lilliefors Significance Correction

Figure 19: Normality test results for accuracy test on the outdoor surface (aggregate concrete, 0 slope, 0 cross-slope).

ANOVA

IndoorForceMeasurement

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	.187	7	.027	.761	.621
Within Groups	8.141	232	.035		
Total	8.328	239			

Figure 20: Results of ANOVA test on the accuracy test on the indoor segment.

ANOVA

OutdoorForceMeasurement

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	.406	7	.058	.872	.529
Within Groups	15.441	232	.067		
Total	15.847	239			

Figure 21: Results of ANOVA test on the accuracy test on the outdoor segment.

ANOVA

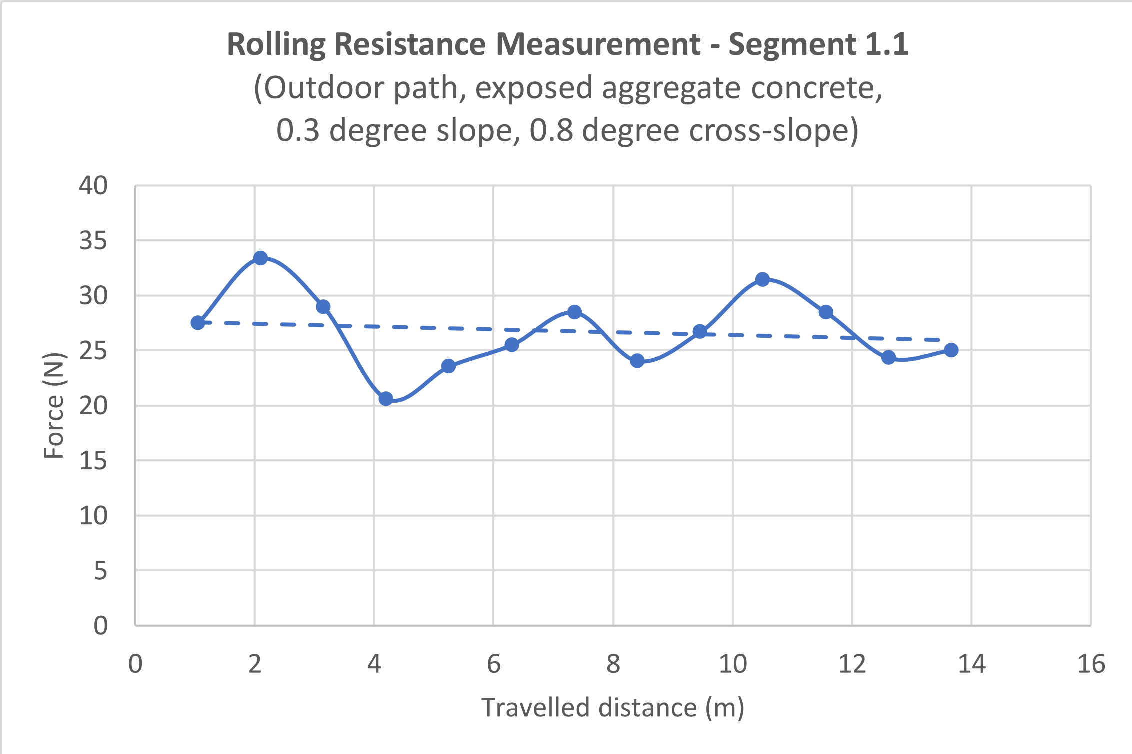
Froll

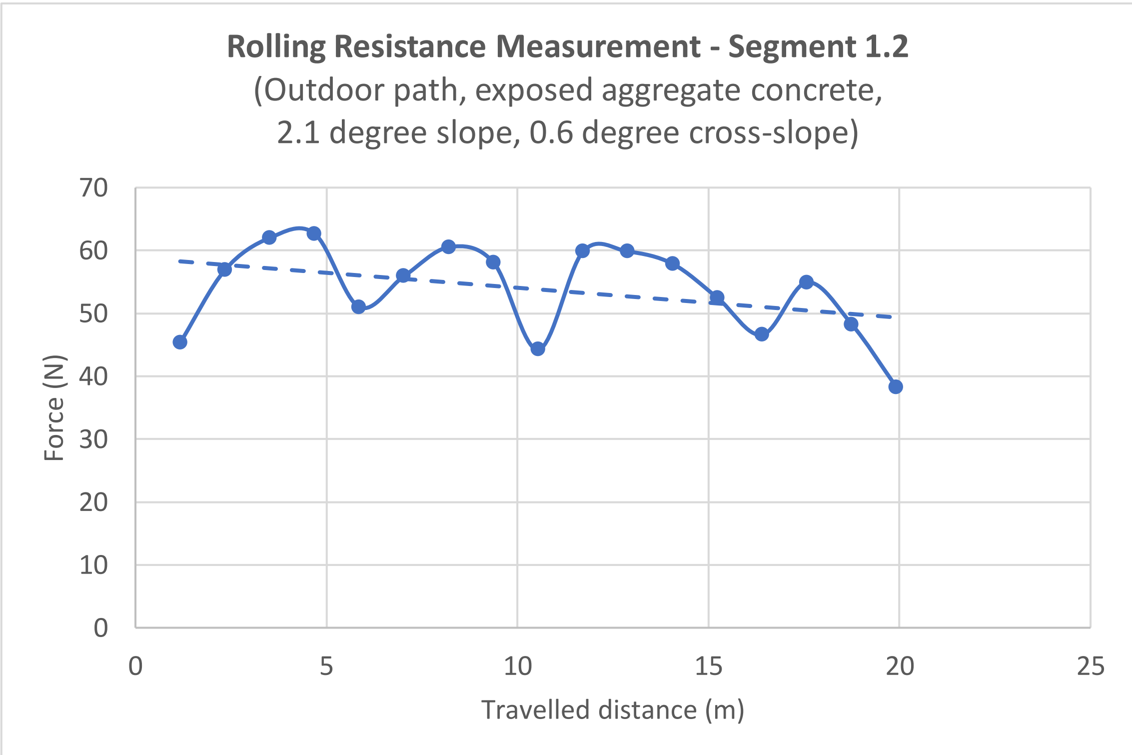
	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	1871.775	9	207.975	910.101	.000
Within Groups	15.996	70	.229		
Total	1887.771	79			

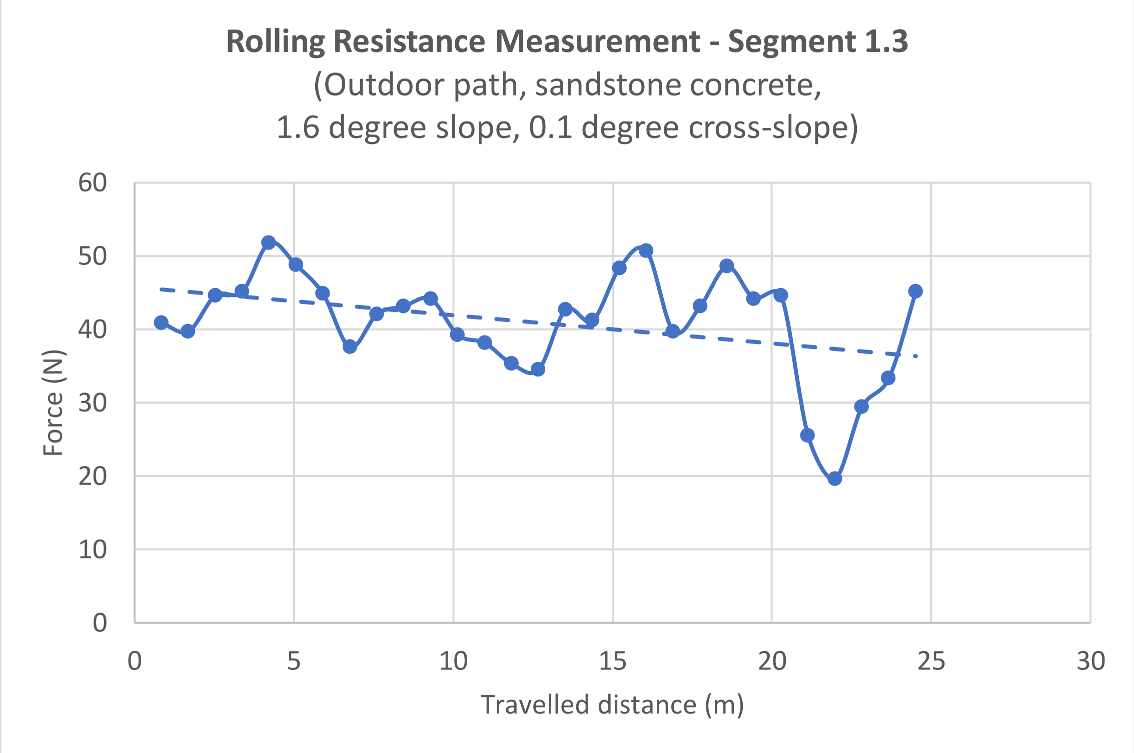
Figure 22: Results of ANOVA test on the rolling resistance of the 5 measured weights in the accuracy test.

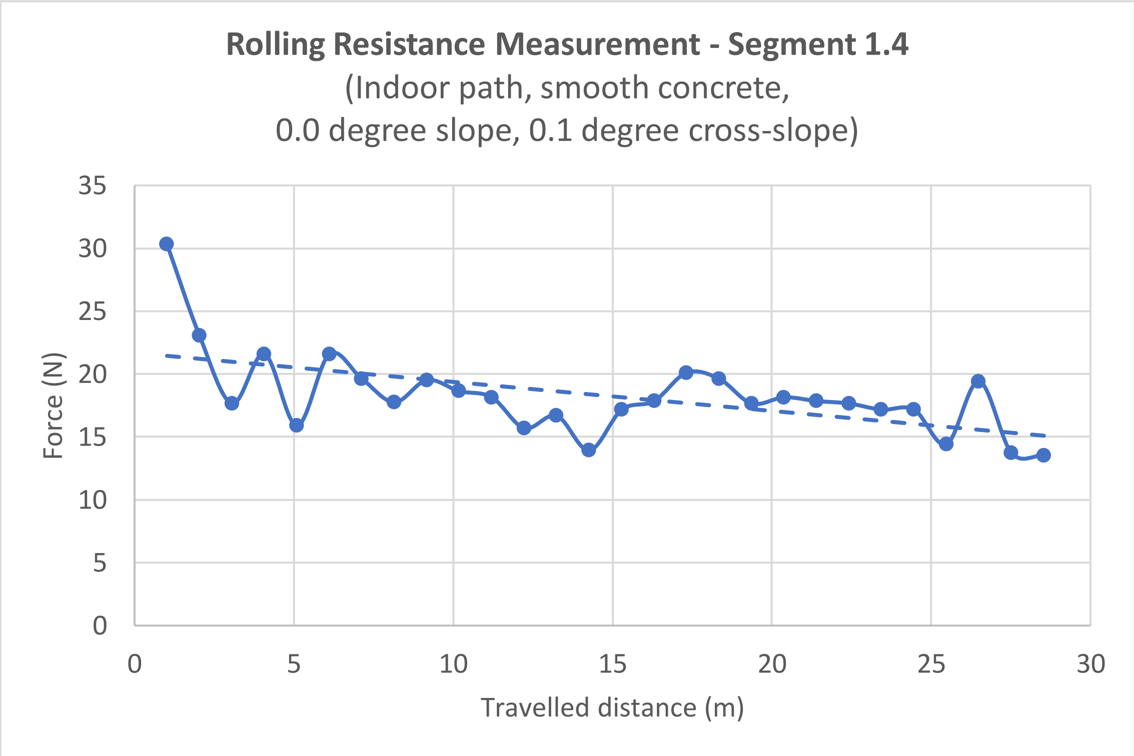
Appendix 6 – Rolling resistance measurement for each segment

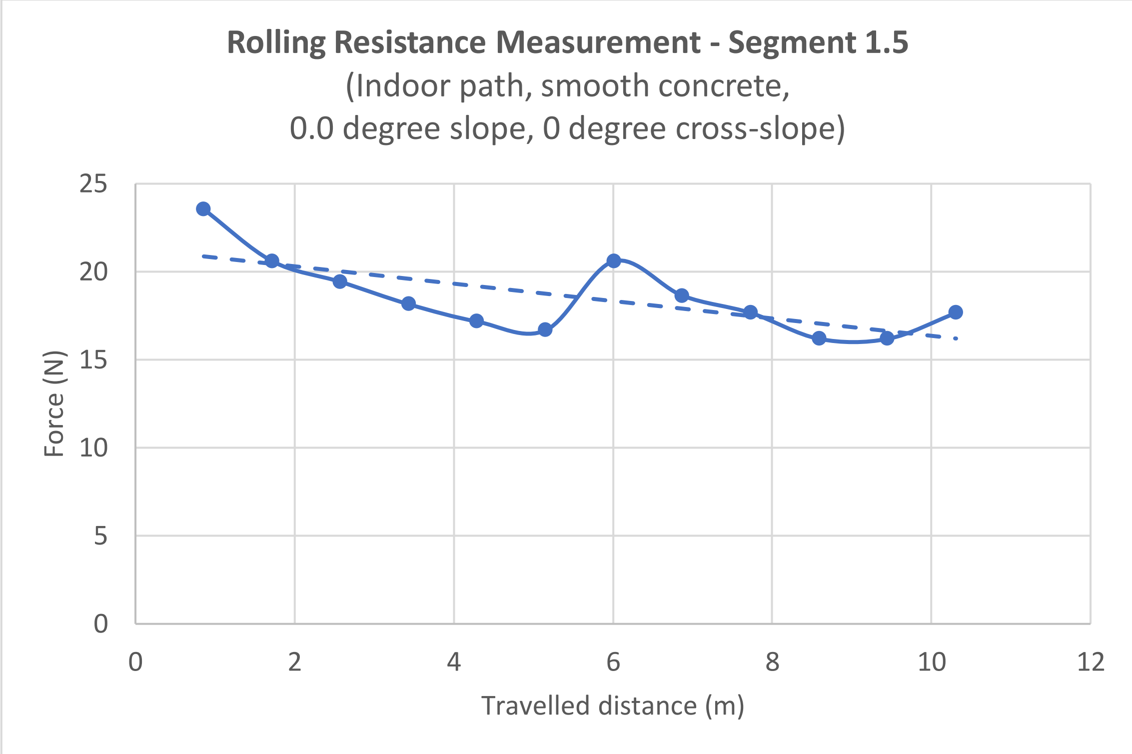
Route 1

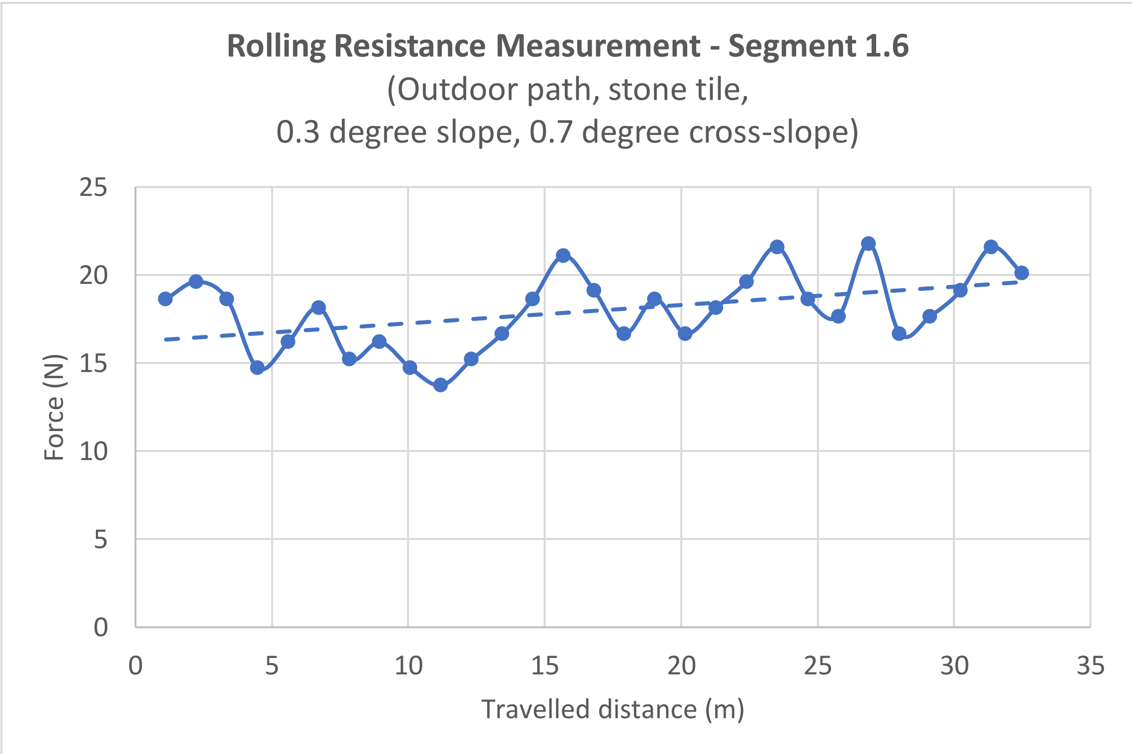


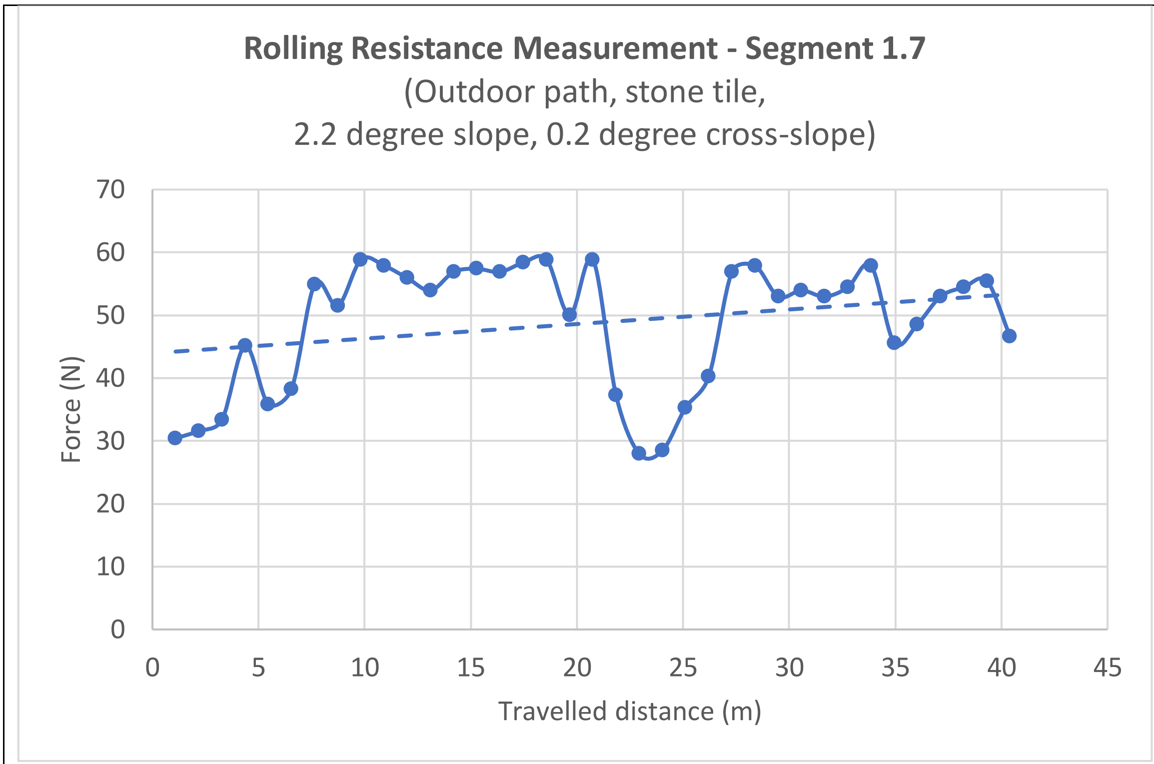



Rolling Resistance Measurement - Segment 1.3
(Outdoor path, sandstone concrete,
1.6 degree slope, 0.1 degree cross-slope)
Force (N)
60
50
40
30
20
10
0
0
5
10
15
20
25
30
Travelled distance (m)

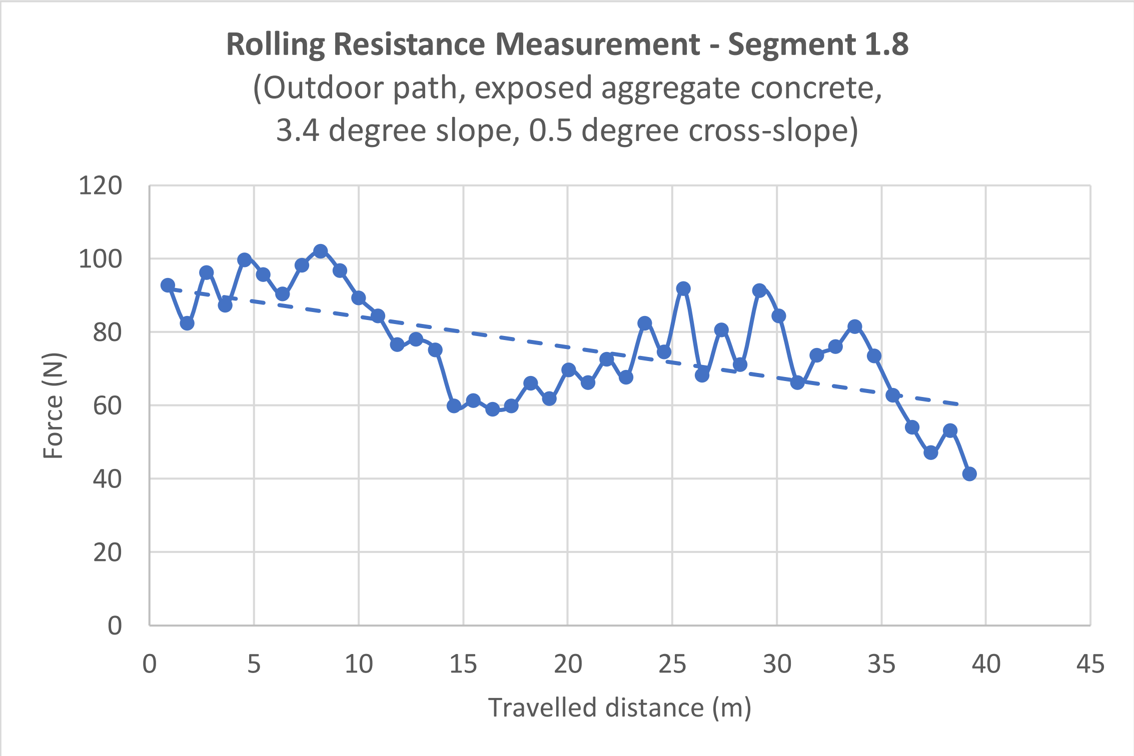

Rolling Resistance Measurement - Segment 1.4
(Indoor path, smooth concrete,
0.0 degree slope, 0.1 degree cross-slope)
Force (N)
35
30
25
20
15
10
5
0
0
5
10
15
20
25
30
Travelled distance (m)


Rolling Resistance Measurement - Segment 1.5
(Indoor path, smooth concrete,
0.0 degree slope, 0 degree cross-slope)
Force (N)
25
20
15
10
5
0
0
2
4
6
8
10
12
Travelled distance (m)

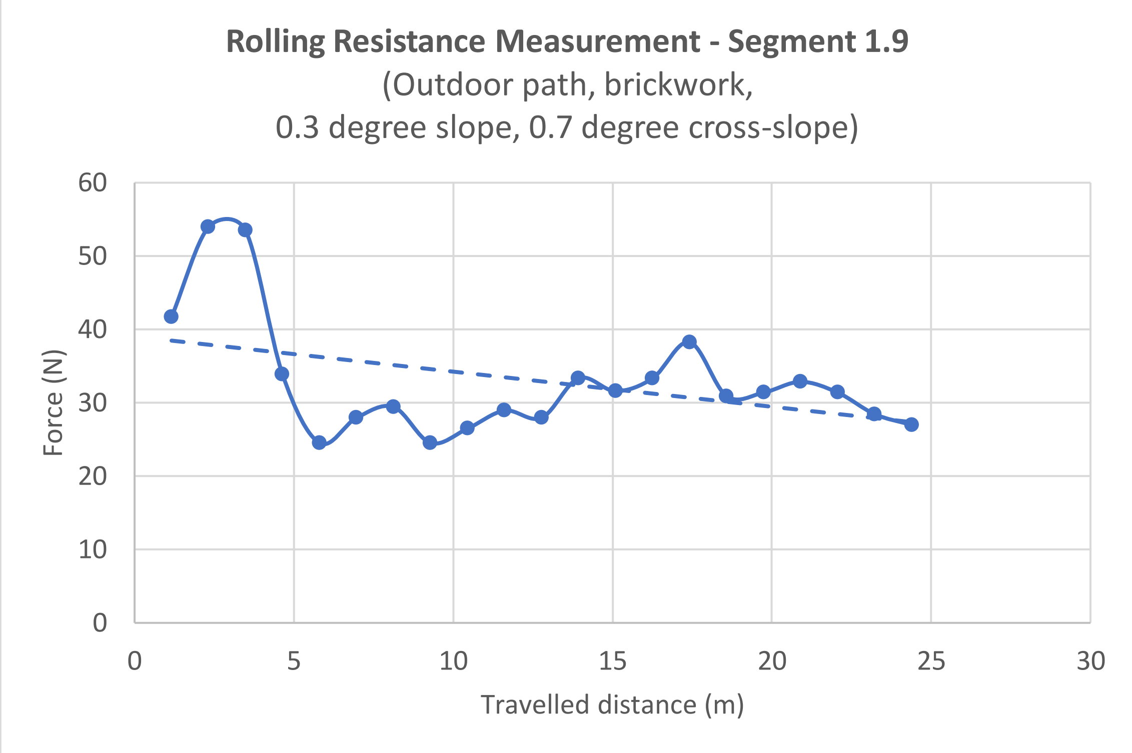

Rolling Resistance Measurement - Segment 1.6
(Outdoor path, stone tile,
0.3 degree slope, 0.7 degree cross-slope)
Force (N)
25
20
15
10
5
0
0
5
10
15
20
25
30
35
Travelled distance (m)



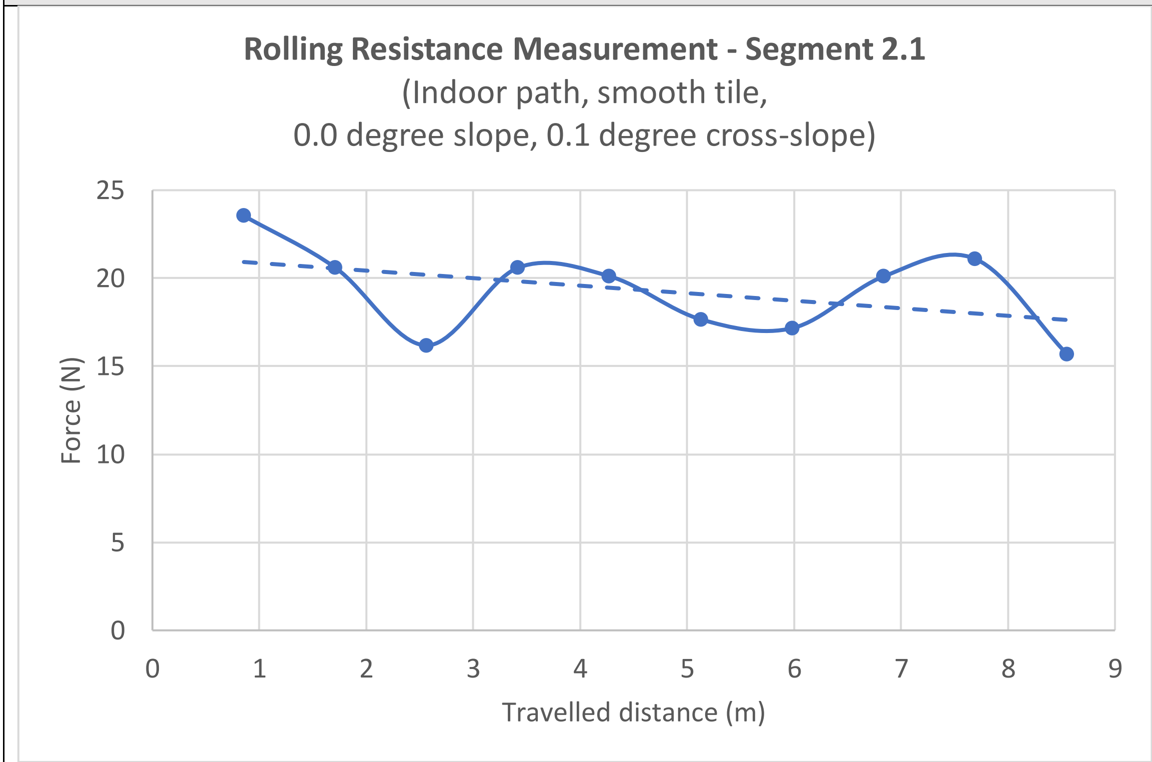
Rolling Resistance Measurement - Segment 1.7
(Outdoor path, stone tile,
2.2 degree slope, 0.2 degree cross-slope)
Force (N)
70
60
50
40
30
20
10
0
0
5
10
15
20
25
30
35
40
45
Travelled distance (m)

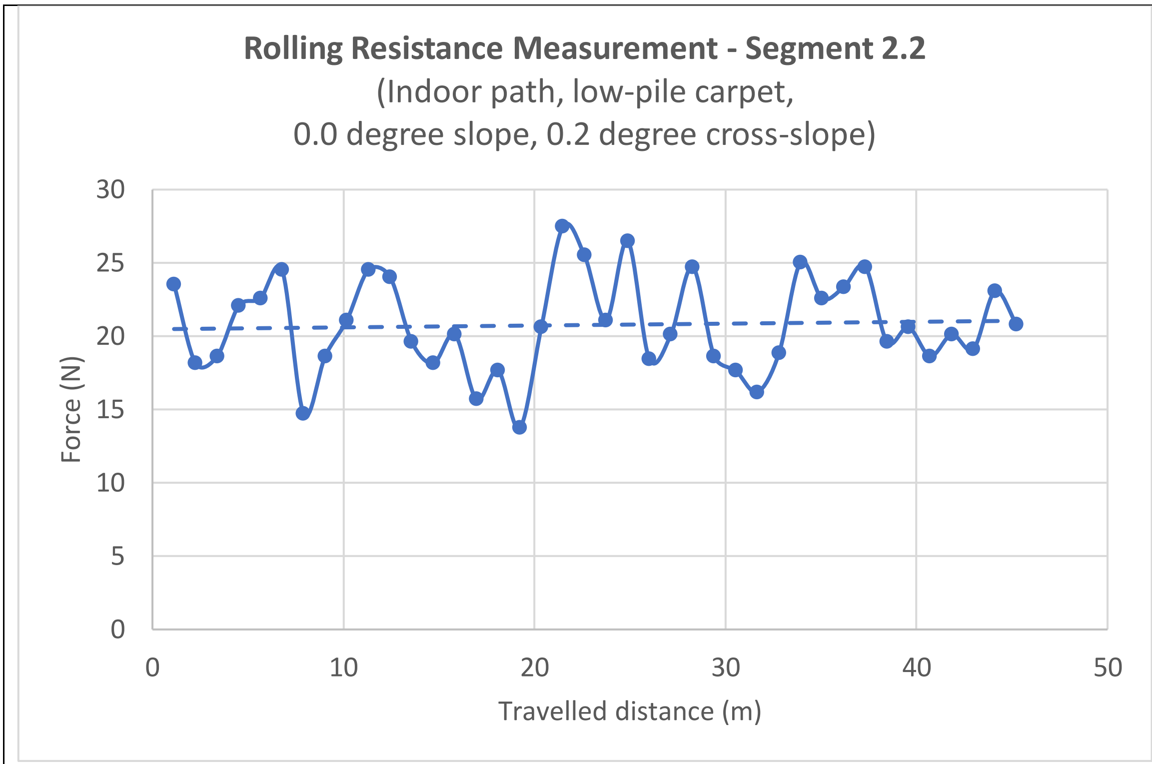


Rolling Resistance Measurement - Segment 1.8
(Outdoor path, exposed aggregate concrete,
3.4 degree slope, 0.5 degree cross-slope)
Force (N)
120
100
80
60
40
20
0
0
5
10
15
20
25
30
35
40
45
Travelled distance (m)

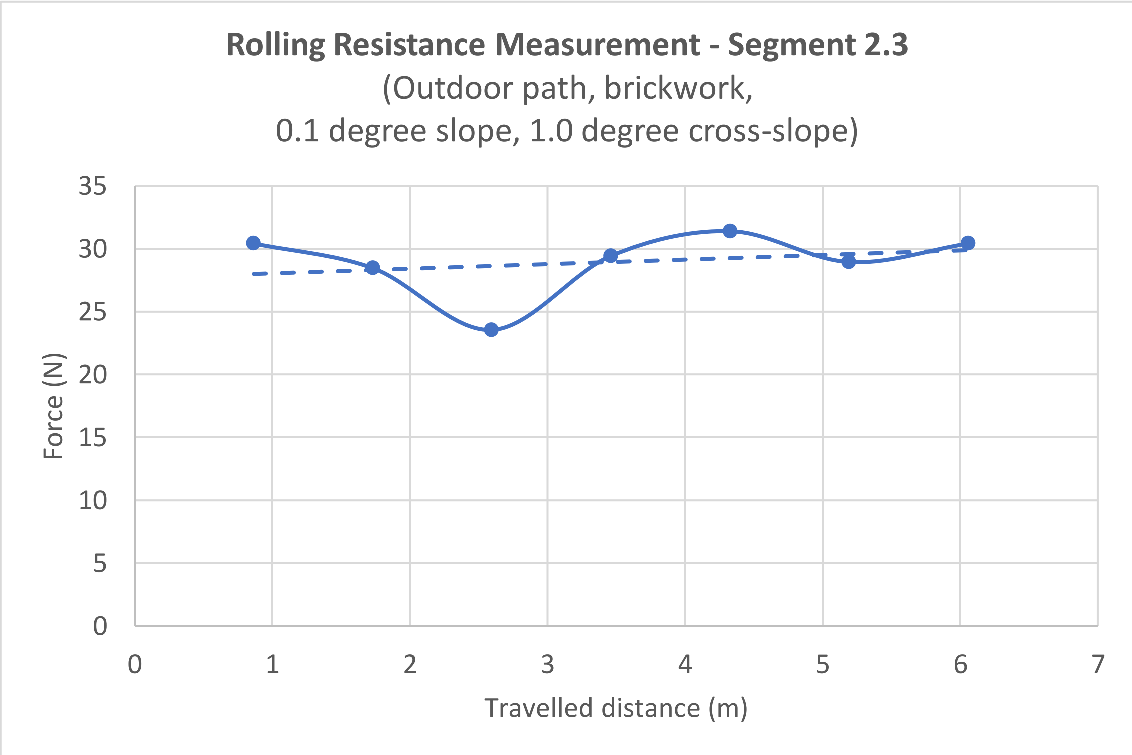

Rolling Resistance Measurement - Segment 1.9
(Outdoor path, brickwork,
0.3 degree slope, 0.7 degree cross-slope)
Force (N)
0
10
20
30
40
50
60
0
5
10
15
20
25
30
Travelled distance (m)

Route 2

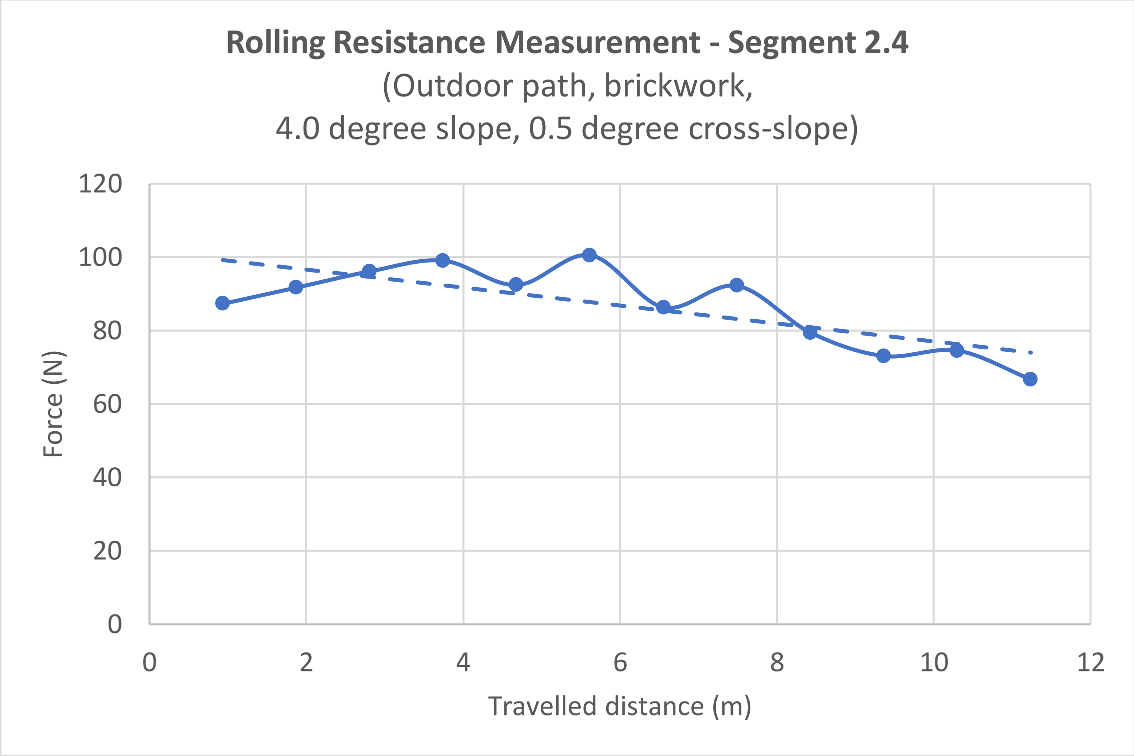

Rolling Resistance Measurement - Segment 2.1
(Indoor path, smooth tile,
0.0 degree slope, 0.1 degree cross-slope)
Force (N)
0
5
10
15
20
25
0
1
2
3
4
5
6
7
8
9
Travelled distance (m)



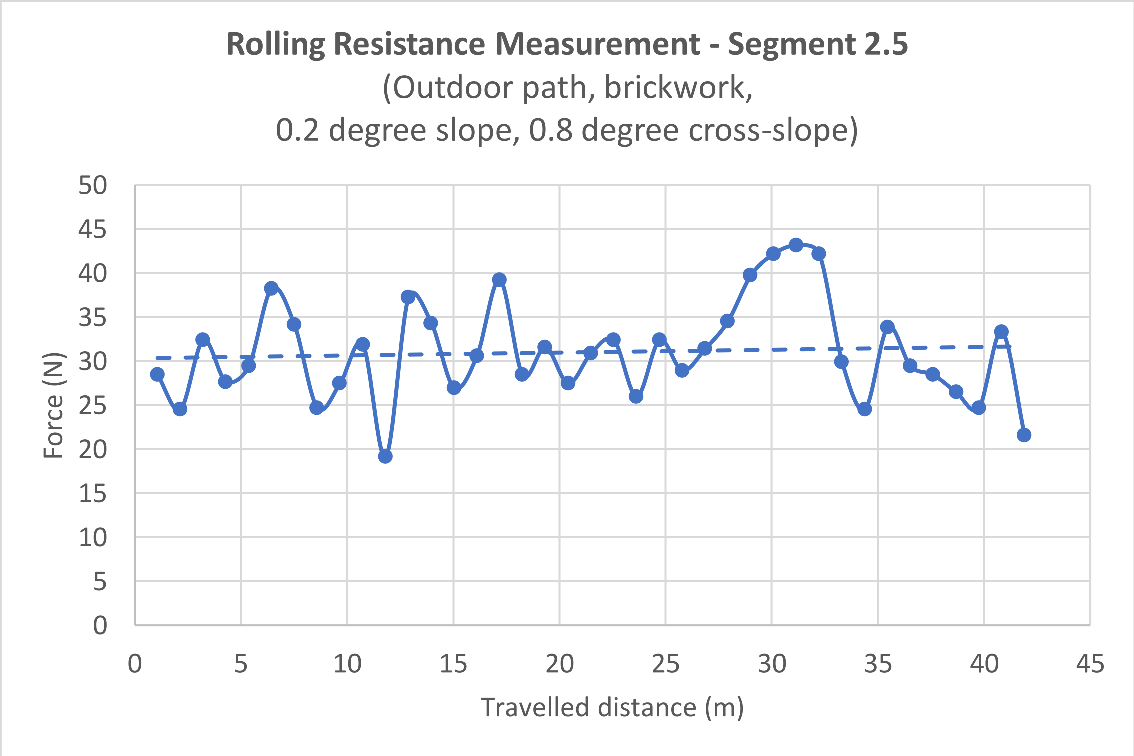
Rolling Resistance Measurement - Segment 2.2
(Indoor path, low-pile carpet,
0.0 degree slope, 0.2 degree cross-slope)
Force (N)
Travelled distance (m)
0
5
10
15
20
25
30
0
10
20
30
40
50



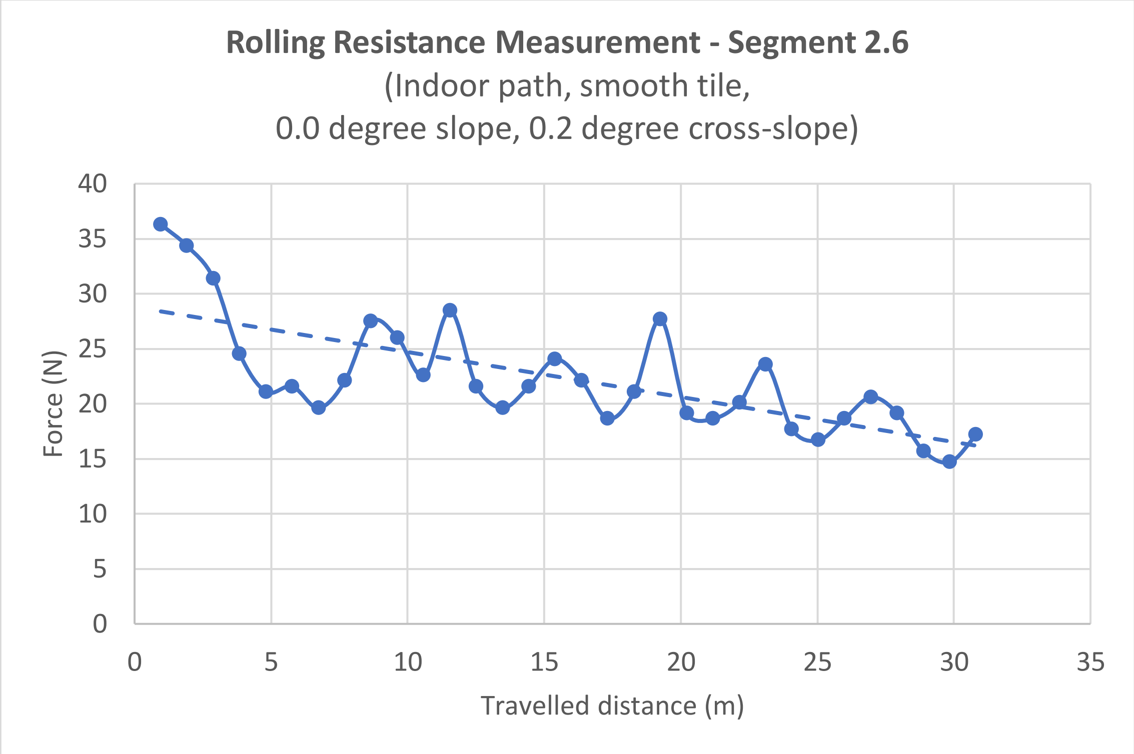
Rolling Resistance Measurement - Segment 2.3
(Outdoor path, brickwork,
0.1 degree slope, 1.0 degree cross-slope)
Force (N)
Travelled distance (m)
0
5
10
15
20
25
30
35
0
1
2
3
4
5
6
7



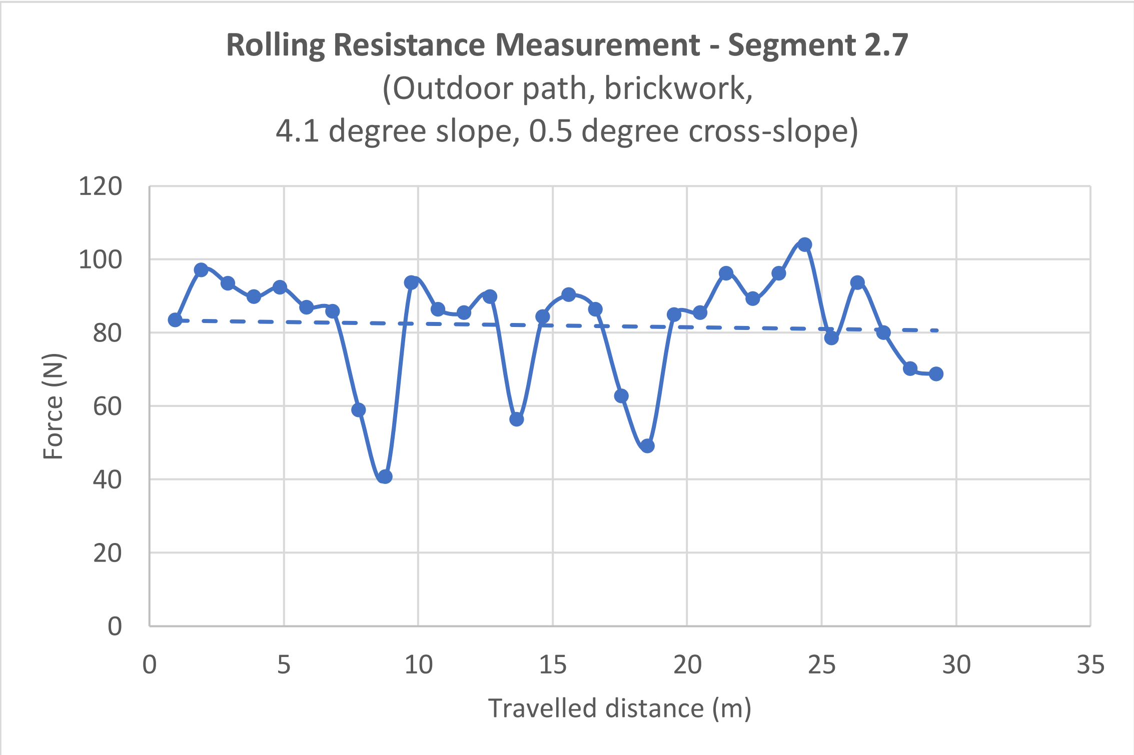
Rolling Resistance Measurement - Segment 2.4
(Outdoor path, brickwork,
4.0 degree slope, 0.5 degree cross-slope)
Force (N)
Travelled distance (m)



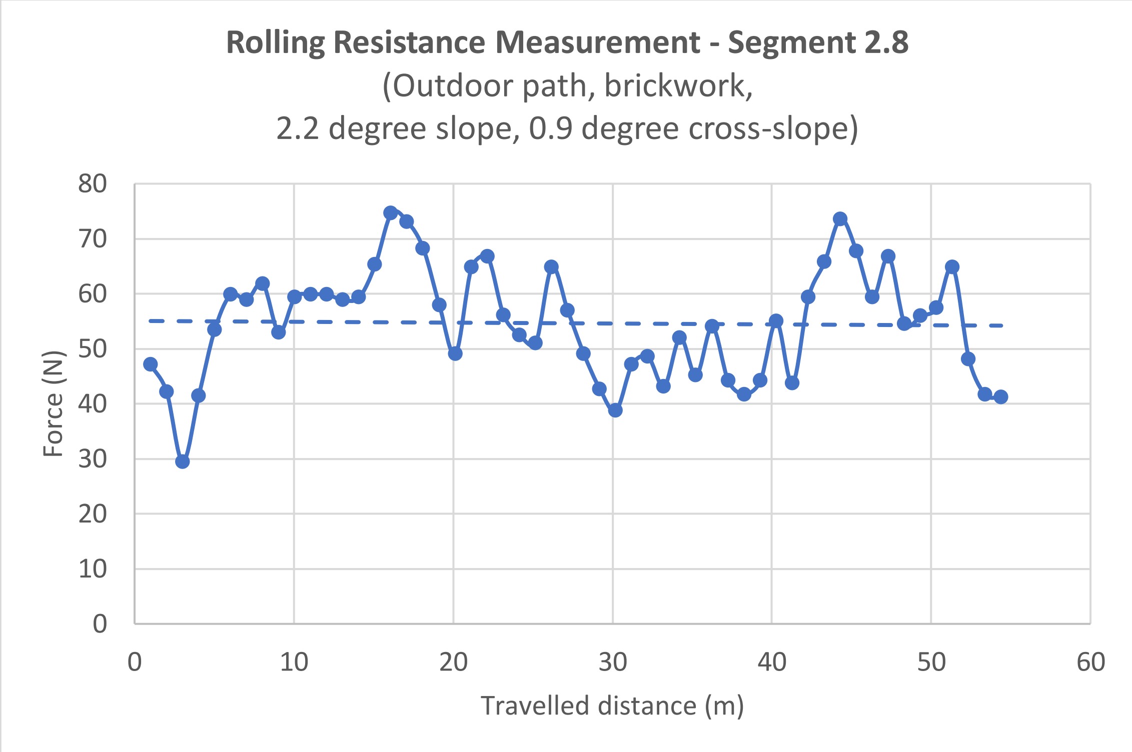
Rolling Resistance Measurement - Segment 2.5
(Outdoor path, brickwork,
0.2 degree slope, 0.8 degree cross-slope)
Force (N)
Travelled distance (m)

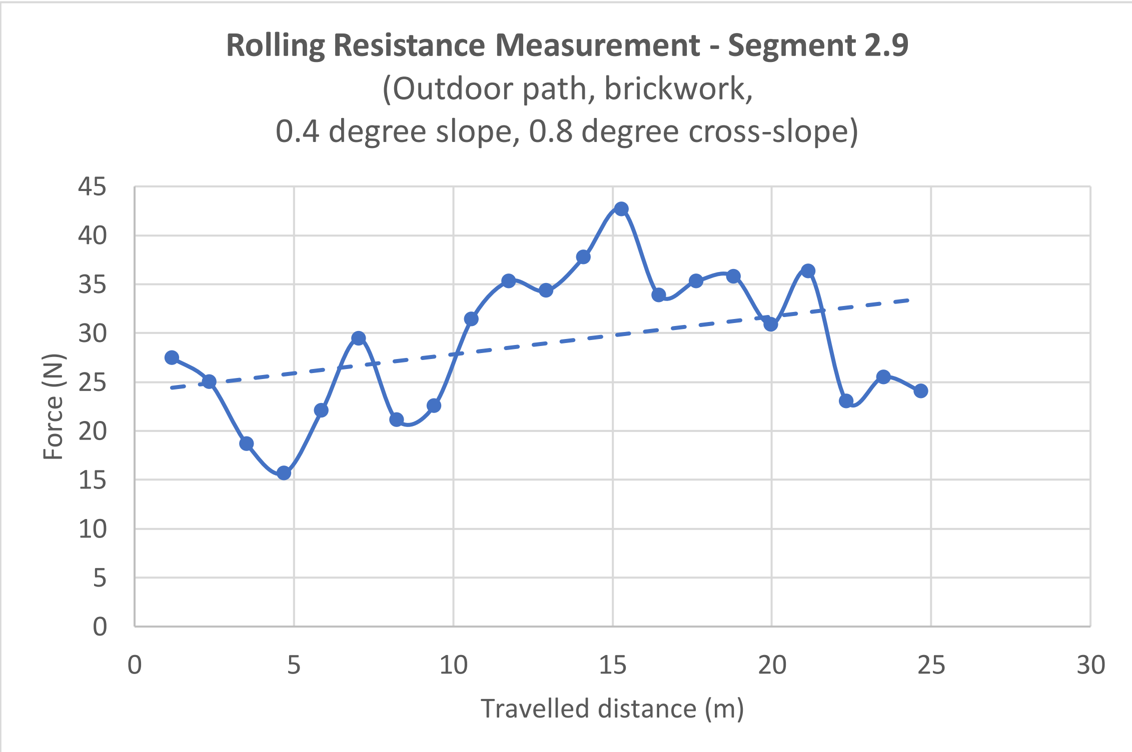


Rolling Resistance Measurement - Segment 2.6
(Indoor path, smooth tile,
0.0 degree slope, 0.2 degree cross-slope)
Force (N)
40
35
30
25
20
15
10
5
0
0
5
10
15
20
25
30
35
Travelled distance (m)

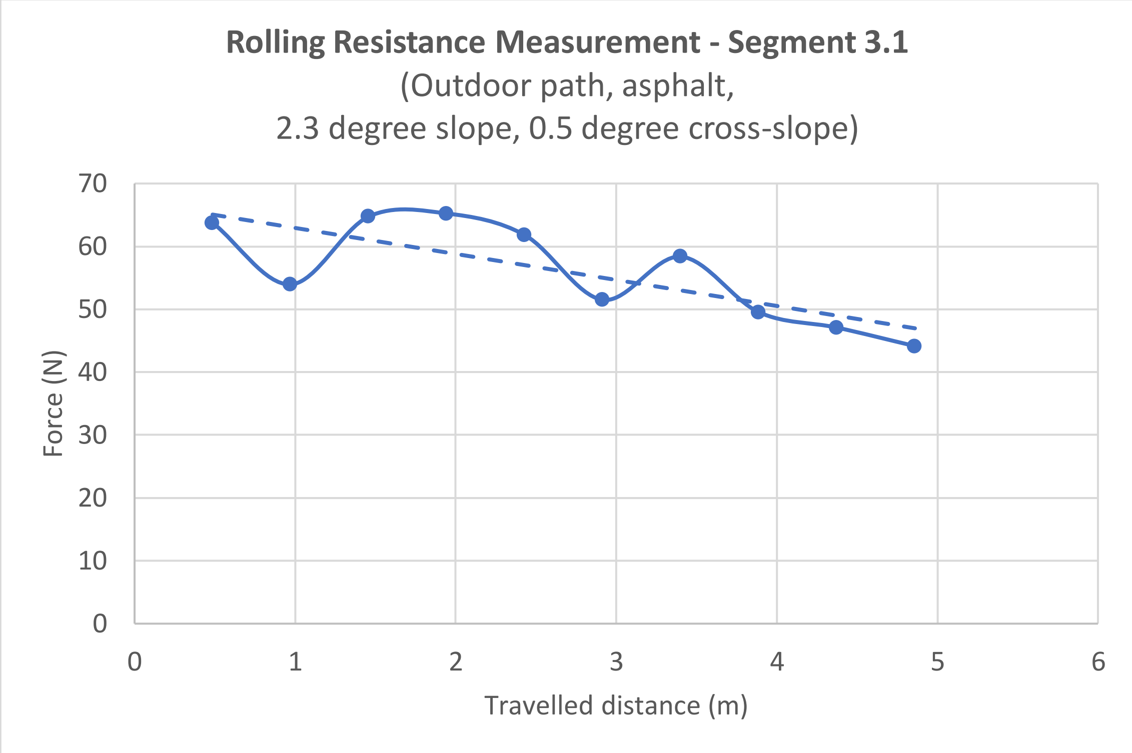


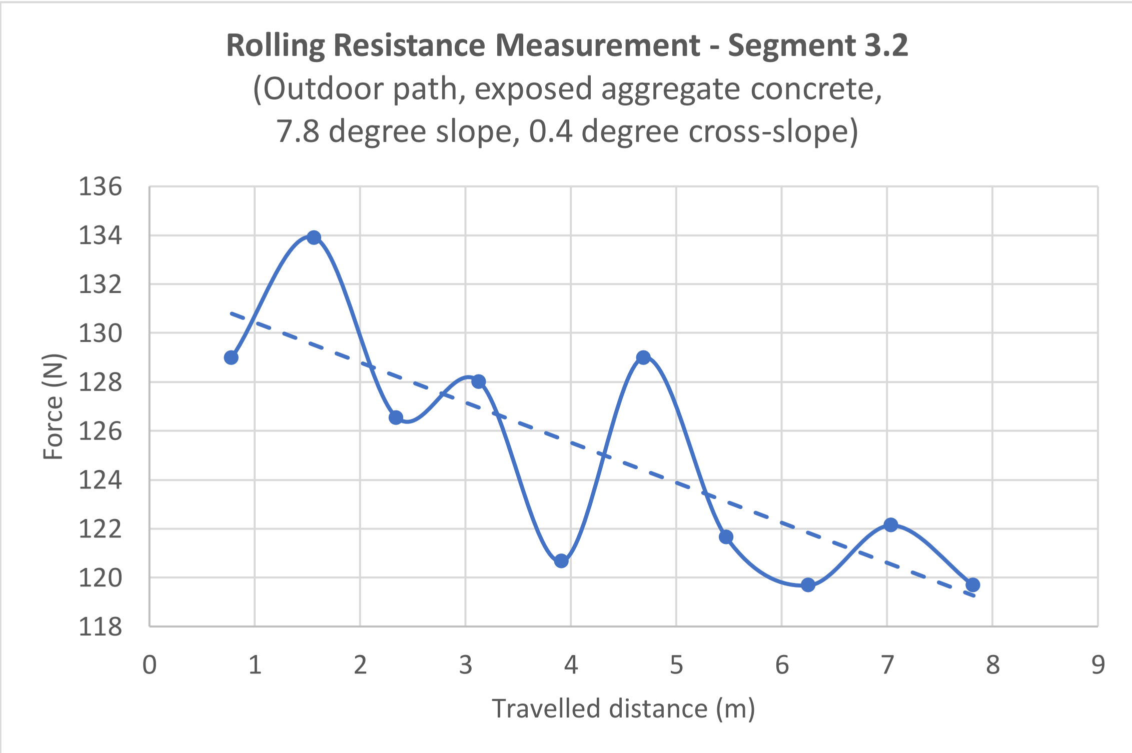
Rolling Resistance Measurement - Segment 2.7
(Outdoor path, brickwork,
4.1 degree slope, 0.5 degree cross-slope)
Force (N)
120
100
80
60
40
20
0
0
5
10
15
20
25
30
35
Travelled distance (m)

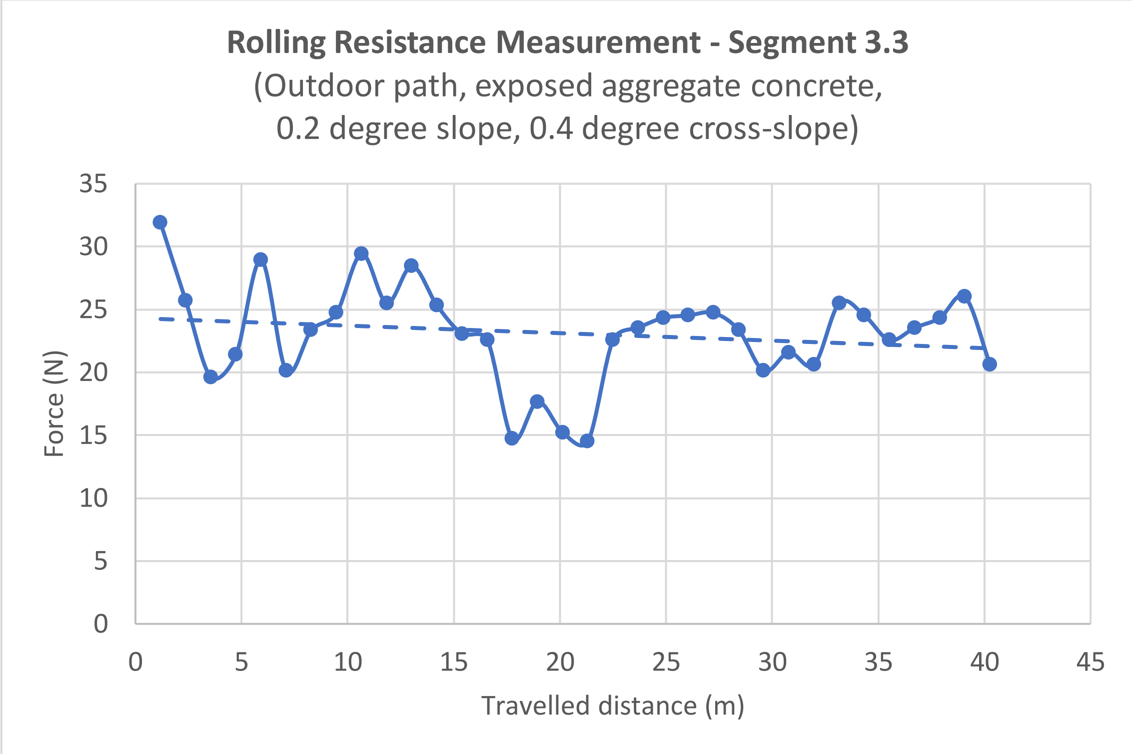

Rolling Resistance Measurement - Segment 2.8
(Outdoor path, brickwork,
2.2 degree slope, 0.9 degree cross-slope)
Force (N)
0
10
20
30
40
50
60
70
80
0
10
20
30
40
50
60
Travelled distance (m)


Rolling Resistance Measurement - Segment 2.9
(Outdoor path, brickwork,
0.4 degree slope, 0.8 degree cross-slope)
Force (N)
0
5
10
15
20
25
30
35
40
45
0
5
10
15
20
25
30
Travelled distance (m)

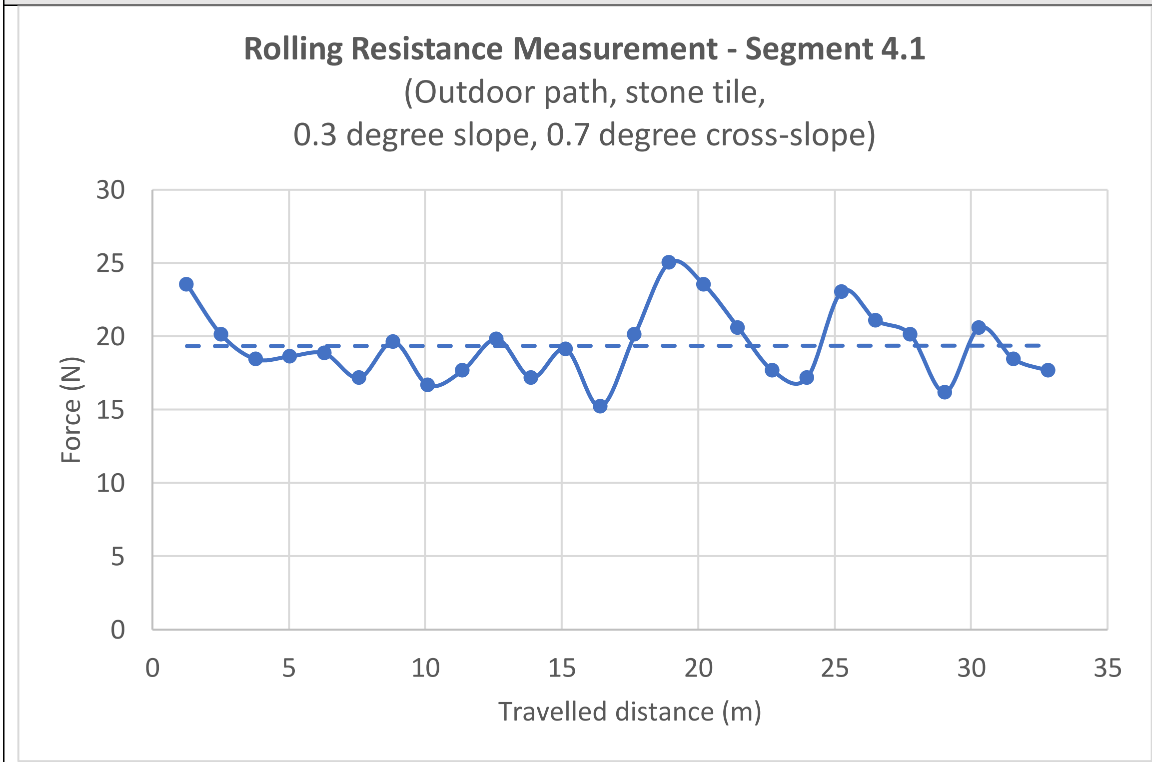
Route 3

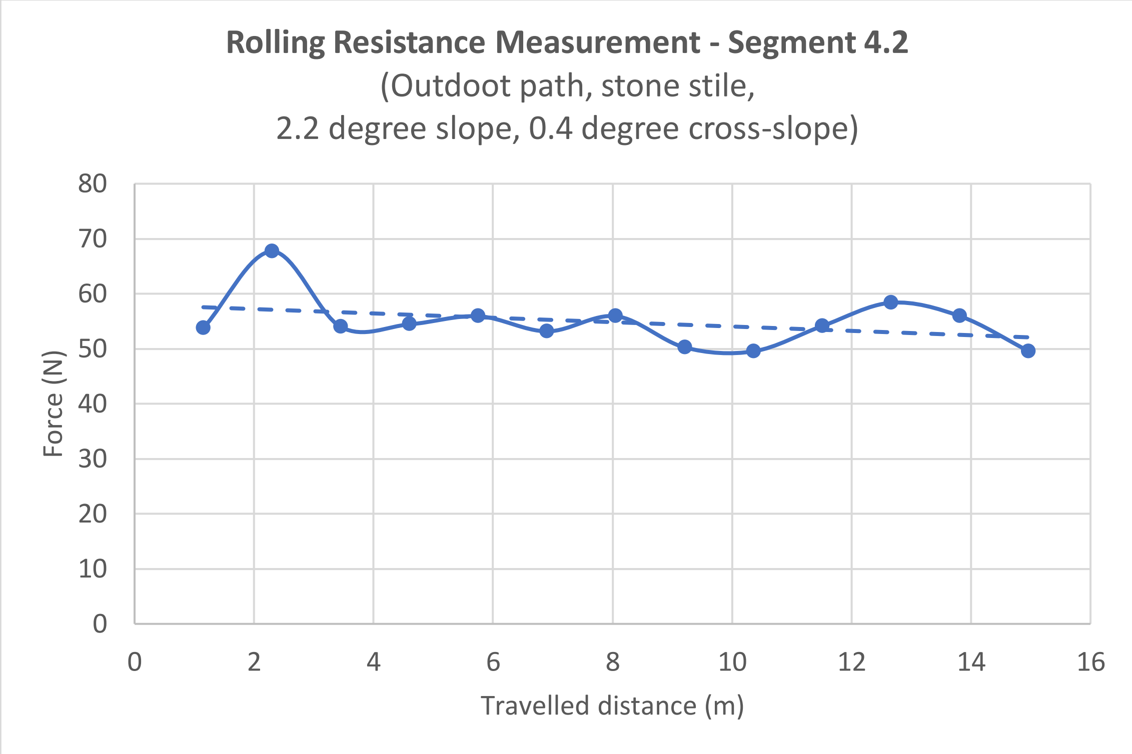

Rolling Resistance Measurement - Segment 3.1
(Outdoor path, asphalt,
2.3 degree slope, 0.5 degree cross-slope)
Force (N)
70
60
50
40
30
20
10
0
0
1
2
3
4
5
6
Travelled distance (m)

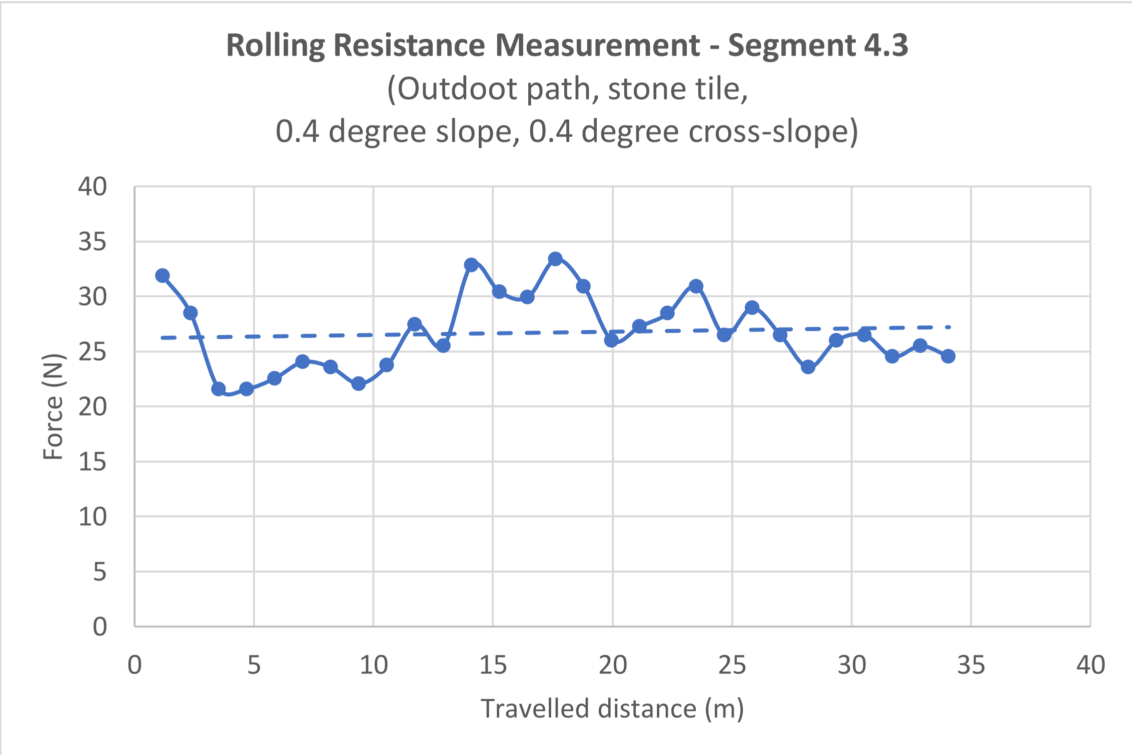

Rolling Resistance Measurement - Segment 3.2
(Outdoor path, exposed aggregate concrete,
7.8 degree slope, 0.4 degree cross-slope)
Force (N)
136
134
132
130
128
126
124
122
120
118
0
1
2
3
4
5
6
7
8
9
Travelled distance (m)

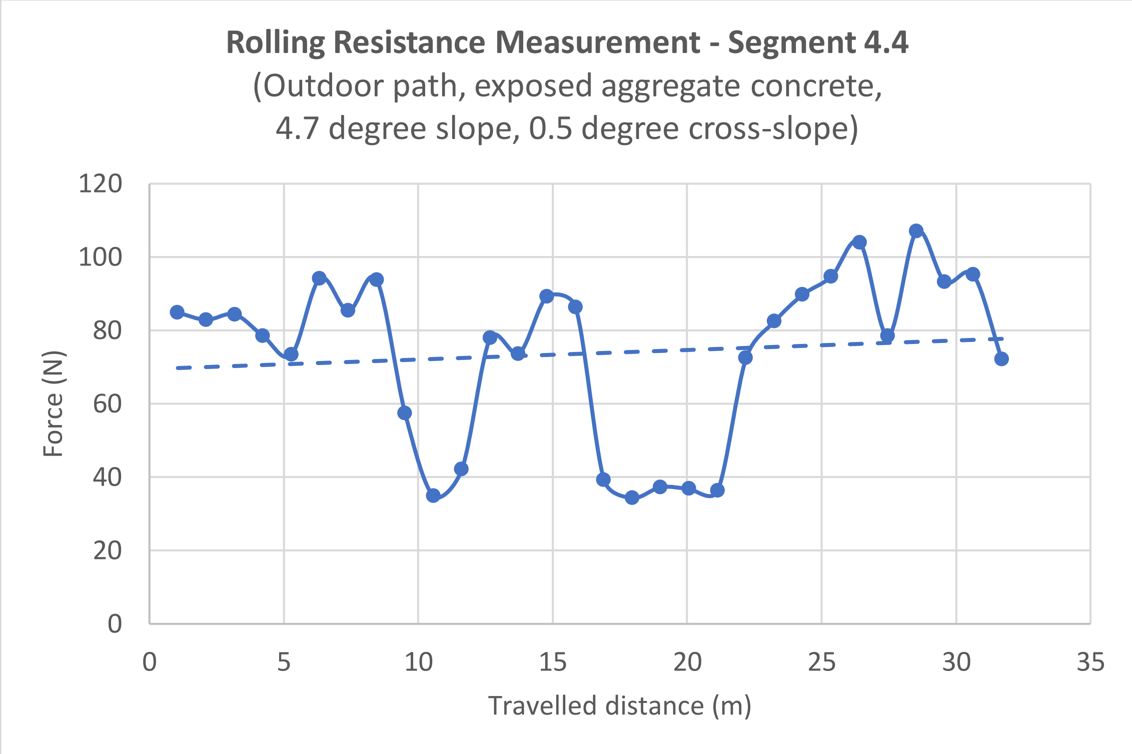

Rolling Resistance Measurement - Segment 3.3
(Outdoor path, exposed aggregate concrete,
0.2 degree slope, 0.4 degree cross-slope)
Force (N)
Travelled distance (m)
0
5
10
15
20
25
30
35
40
45

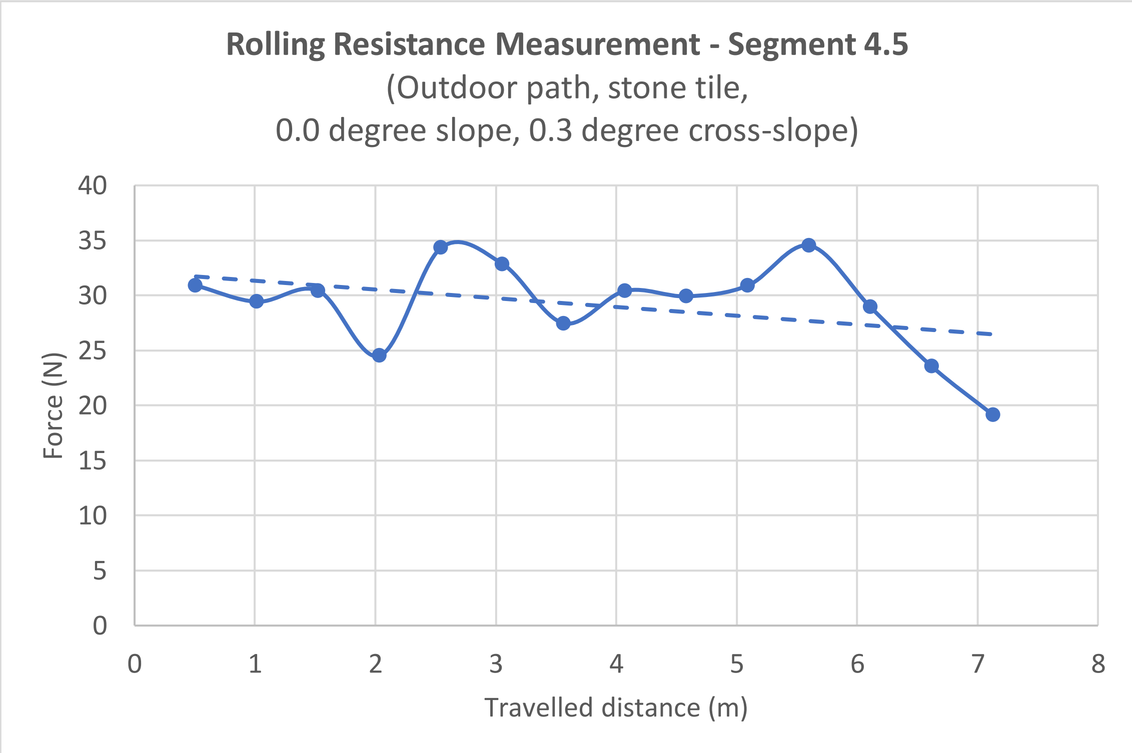
Route 4


Rolling Resistance Measurement - Segment 4.1
(Outdoor path, stone tile,
0.3 degree slope, 0.7 degree cross-slope)
Force (N)
Travelled distance (m)
0
5
10
15
20
25
30
35

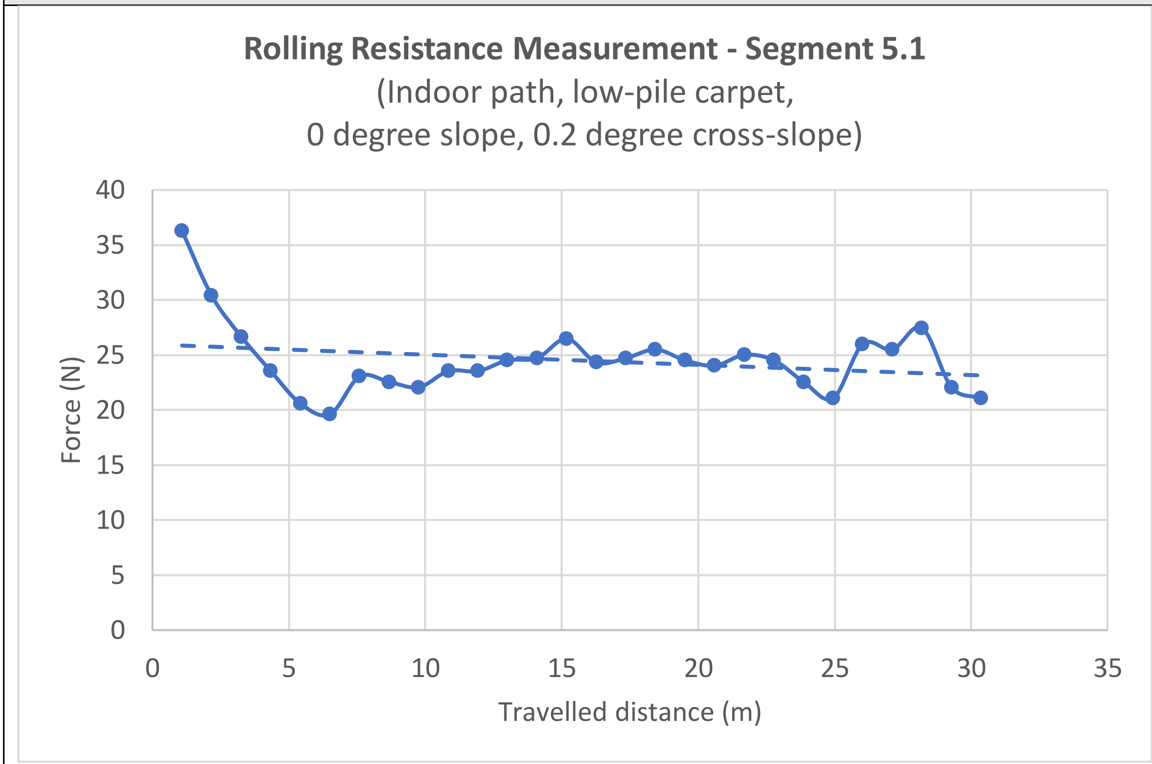

Rolling Resistance Measurement - Segment 4.2
(Outdoot path, stone stile,
2.2 degree slope, 0.4 degree cross-slope)
Force (N)
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
16
Travelled distance (m)


Rolling Resistance Measurement - Segment 4.3
(Outdoot path, stone tile,
0.4 degree slope, 0.4 degree cross-slope)
Force (N)
40
35
30
25
20
15
10
5
0
0
5
10
15
20
25
30
35
40
Travelled distance (m)


Rolling Resistance Measurement - Segment 4.4
(Outdoor path, exposed aggregate concrete,
4.7 degree slope, 0.5 degree cross-slope)
Force (N)
Travelled distance (m)
0
20
40
60
80
100
120
0
5
10
15
20
25
30
35

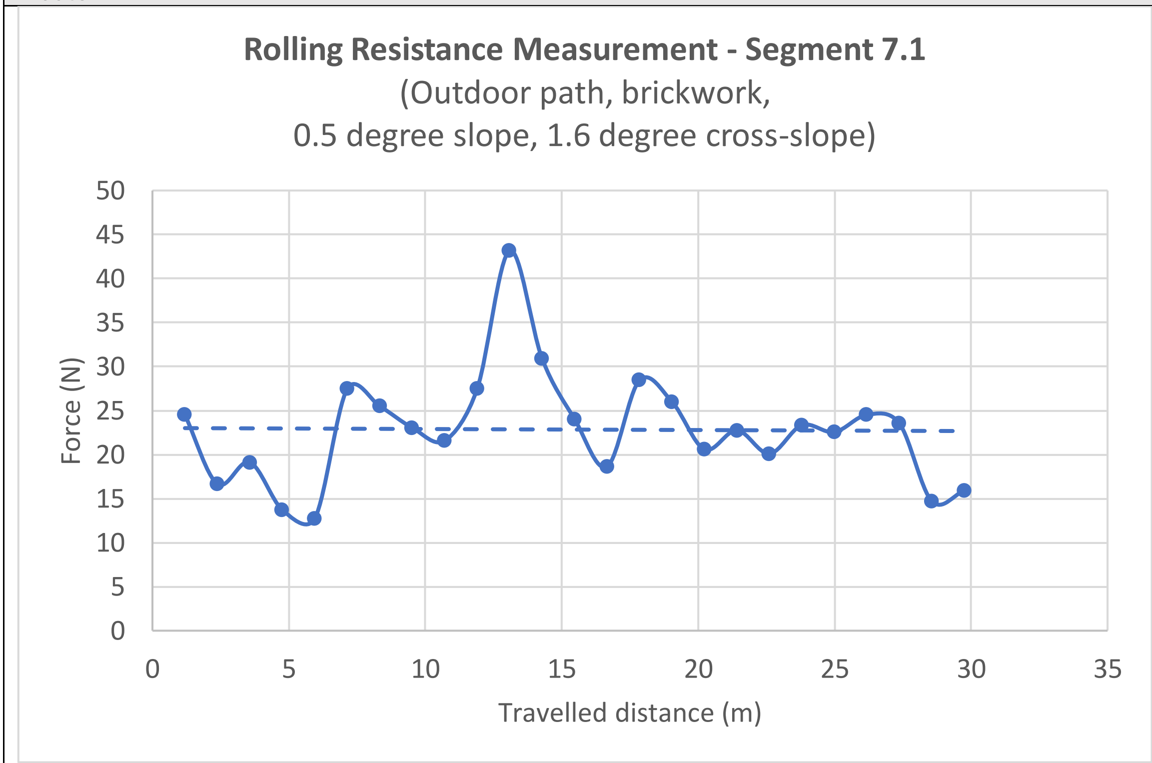

Rolling Resistance Measurement - Segment 4.5
(Outdoor path, stone tile,
0.0 degree slope, 0.3 degree cross-slope)
Force (N)
Travelled distance (m)
0
5
10
15
20
25
30
35
40
0
1
2
3
4
5
6
7
8

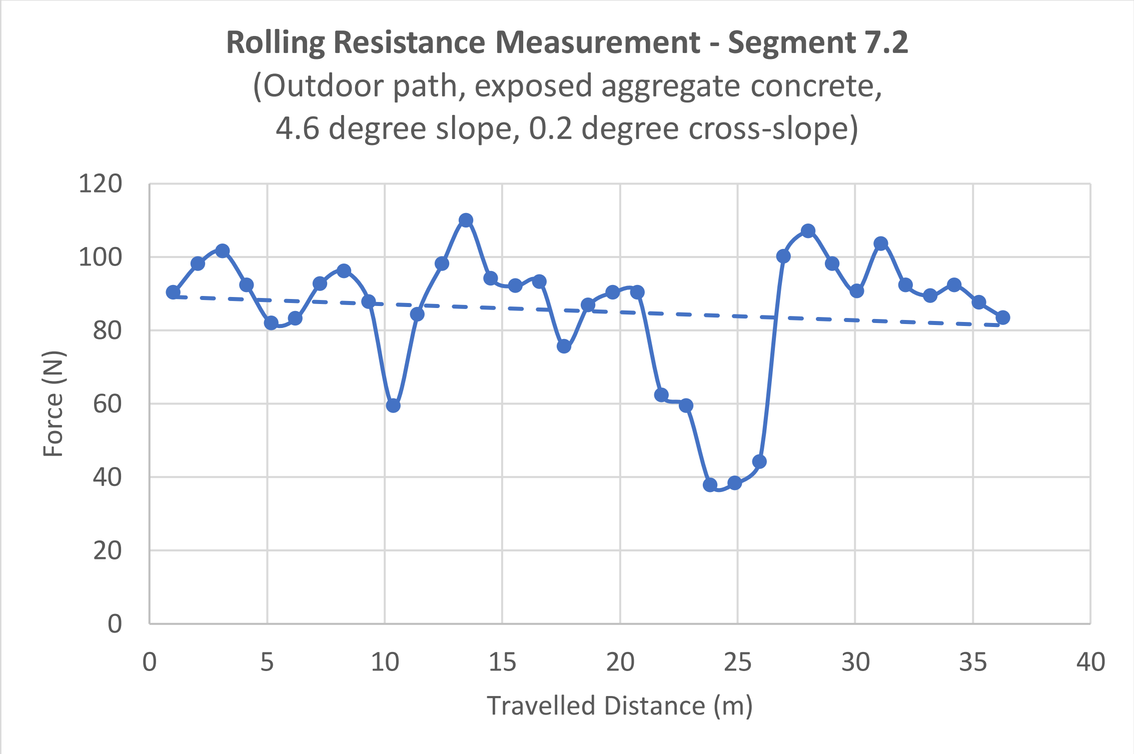
Route 5



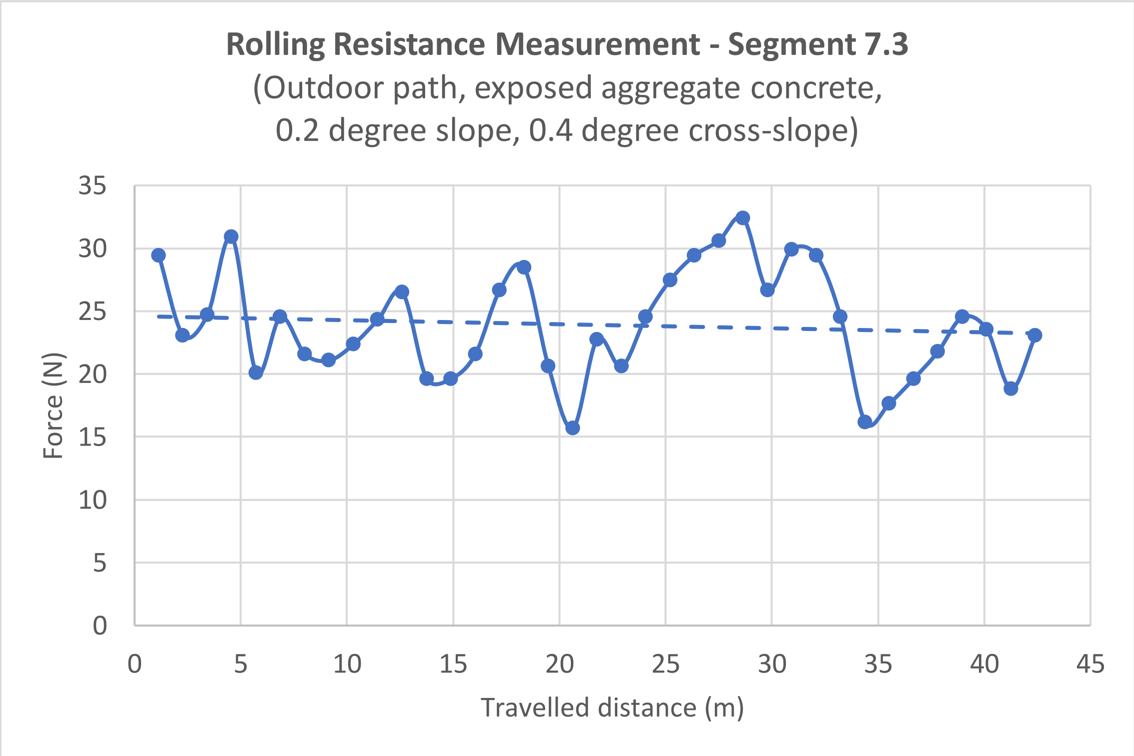
Route 6 (Not available due to temporary work in the route)

Route 7





Rolling Resistance Measurement - Segment 7.2
(Outdoor path, exposed aggregate concrete,
4.6 degree slope, 0.2 degree cross-slope)
120
100
80
60
40
20
0
Force (N)
0
5
10
15
20
25
30
35
40
Travelled Distance (m)



Rolling Resistance Measurement - Segment 7.3
(Outdoor path, exposed aggregate concrete,
0.2 degree slope, 0.4 degree cross-slope)
35
30
25
20
15
10
5
0
Force (N)
0
5
10
15
20
25
30
35
40
45
Travelled distance (m)

Appendix 7 – Energy cost of the sample routes

Route	Segment	Segment length (m)	Average rolling resistance (N)	Segmental energy cost (Joules)	Slope direction (from A to B)	Total energy cost from A to B (Joules)	Total energy cost from B to A (Joules)
1	1.1	13.7	26.8	365.7	-	3467.9	8482.1
	1.2	19.9	53.9	1072.7	Down		
	1.3	24.5	40.9	1002.3	Up		
	1.4	28.6	18.2	521.5	-		
	1.5	10.3	18.5	190.9	-		
	1.6	32.5	18.0	583.6	-		
	1.7	40.4	48.8	1970.6	Down		
	1.8	39.2	75.8	2973.2	Down		
	1.9	24.4	33.0	803.9	-		
2	2.1	8.6	19.3	164.6	-	4954.2	9352.4
	2.2	45.2	20.8	939.6	-		
	2.3	6.1	28.9	175.5	-		
	2.4	11.2	86.6	973.1	Up		
	2.5	41.9	31.0	1300.3	-		
	2.6	30.8	22.3	686.9	-		
	2.7	29.3	82.0	2400.2	Down		
	2.8	54.4	54.6	2971.1	Down		
	2.9	24.7	29.0	714.2	-		
3	3.1	4.7	56.0	267.3	Up	2173.2	929.4
	3.2	7.8	124.9	976.5	Up		
	3.3	40.3	23.0	929.4	-		
4	4.1	32.8	19.4	635.5	-	4089.1	2573.7
	4.2	15.0	54.8	821.4	Down		
	4.3	34.1	26.7	910.7	-		
	4.4	31.7	73.7	2336.8	Up		
	4.5	7.1	29.1	206.1	-		
5	5.1	30.4	24.5	744.3	-	744.3	744.3
6	*Not available due to temporary work in the route.*						
7	7.1	29.8	22.8	679.7	-	4789.1	1693.5
	7.2	36.3	85.2	3095.6	Up		
	7.3	42.4	23.9	1013.8	-		

Note: The segmental energy cost is computed with the scatter plots graph and the trendline shown in Appendix 6 (not directly with the average rolling resistance).

Appendix 8 – Colour-coding for energy cost level

Energy cost of all segments (J) *(30 segments sorted from low to high and divided into 3 groups)*	Route	Segment	Energy cost (from A to B) (J)	Energy cost (from B to A) (J)
164.6		1.1	365.7	365.7
175.5		1.2	0	1072.7
190.9		1.3	1002.3	0
206.1		1.4	521.5	521.5
267.3	1	1.5	190.9	190.9
365.7		1.6	583.6	583.6
521.5		1.7	0	1970.6
583.6		1.8	0	2973.2
635.5		1.9	803.9	803.9
679.7		2.1	164.6	164.6
686.9		2.2	939.6	939.6
714.2		2.3	175.5	175.5
744.3		2.4	973.1	0
803.9	2	2.5	1300.3	1300.3
821.4		2.6	686.9	686.9
910.7		2.7	0	2400.2
929.4		2.8	0	2971.1
939.6		2.9	714.2	714.2
973.1		3.1	267.3	0
976.5	3	3.2	976.5	0
1002.3		3.3	929.4	929.4
1013.8		4.1	635.5	635.5
1072.7		4.2	0	821.4
1300.3	4	4.3	910.7	910.7
1970.6		4.4	2336.8	0
2336.8		4.5	206.1	206.1
2400.2	5	5.1	744.3	744.3
2971.1		7.1	679.7	679.7
2973.2	7	7.2	3095.6	0
3095.6		7.3	1013.8	1013.8

(Route 6 is not included due to the temporary work in the route.)

Segment count

Red	12
Yellow	17
Green	31
Total	60

Note: When the MWC can free-wheel down the slope, the energy cost is taken as 0 J. This type of segment is also colour-coded as green on the map.