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Comparing travel costs of wheelchair and other passengers in Sydney Train network

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Abstract

Around 33,100 wheelchair users live in Sydney, representing 0.44% of the state's population. While the majority of transport needs of wheelchair users are met by taxis or wheelchair modified vehicles owned by private households, a public transport network comprised of buses, trains and ferries has been adapted to accommodate people with mobility disabilities or restrictions. This paper compares the generalised travel costs of wheelchair users and other passengers in the Sydney Train network. The generalised travel cost approach aims to capture the travel time, out of pocket cost and human effort involved in train trips in the whole journey. In this paper we estimate the broad level travel demands of wheelchair users based upon data from the ABS survey of disabilities, ageing and carers undertaken and observed wheelchair trips. Supply of wheelchair accessibility of Sydney Train network will be examined using station accessibility datasets containing wheelchair accessibility, provision of lift and ramp, accessible amenities, passenger entries and exits in 307 Sydney train stations. Wheelchair riding time, waiting time, on-board time, effort at each stage of a rail trip, fare costs and impacts on train crowding will be modelled at each of travel legs from access, at-station / interchanges, egress, cross platform or change platform transfers. The generalised travel costs will be estimated for a 'synthetic' Sydney train trip for wheelchair and other passengers. The framework, parameters and generalised travel costs developed in this paper will contribute to improve economic appraisal of public transport facilities for mobility accessibility and will provide insightful knowledge for planning disability facilities in public transport network. The last section of the paper provides a brief overview of how dynamic pedestrian modelling can be used to assess the cost of travel within a station (or a modelled area) for wheelchair users in great detail; the appendix to this paper provides an example of generalised journey time and social cost from a typical pedestrian modelling tool, considering at micro level all costs incurred by both wheelchair and non-wheelchair passengers in terms of monetised waiting times, effort and level of service experienced.

1. Introduction

Provision of wheelchair access to public transport is a part of obligations under the Disability Discrimination Act 1992 (the DDA). The accessible public transport broadly refers to infrastructure accessibility and conveyance accessibility. Accessible infrastructure provides a person with disability with accessible paths, stairways, ramps, underpass or overpasses to stations, accessible signs for entries, exits, ticketing and amenities, and finally accessible maps and timetables at train stations. Accessible conveyance provides a person with disability with capacity to move from a platform onto the carriage and back again, allocated seats or wheelchair spaces inside the carriage (Allen Consulting Group 2009).

1.1. Conveyance accessibility

All Sydney trains are accessible using a platform to train boarding ramp. Station staff provides boarding and alighting assistance to wheelchair passengers by setting up and collecting the removable boarding ramp. 100% of Sydney Train rolling stock is accessible for people who are mobility impaired. New Waratah trains offer enhanced facilities including wheelchair spaces, priority seats for elderly and less mobile passengers and Accessible Emergency Help Points.

1.2. Infrastructure accessibility

The compliance for Disability Standards for accessible public transport requires 55% of infrastructure accessible by 2012 and 100% infrastructure accessible by 2022 (TfNSW 2012). Accessible transport is a 'whole of journey' issue. If the starting station is accessible but the destination station is inaccessible, the journey is still considered inaccessible. All Sydney train stations classified as wheelchair accessible provide a level, lift or ramp access to all platforms. However, not every entrance of accessible stations is wheelchair accessible. Thus, wheelchair passengers may have fewer station entrances than other passengers, thus frequently having to travel longer distances than other passengers to reach the platforms.

A rail trip can be divided into individual trip legs that includes access trip, at station, on-board and egress trip. All access and egress trips are considered wheelchair accessible and 100% of rolling stock provide wheelchair accessible vestibules. From a whole journey point of view, the wheelchair accessibility of a rail journey is defined by the station accessibility. Lifts and low gradient access ramps are key infrastructure for station accessibility. Australian Standards (AS 1428) for access and mobility stipulate 1:10 to be the maximum gradient of a step ramp for wheelchair access; however, portable ramps used by station staff to help passengers on wheelchairs boarding and exiting trains are often 1:8 or steeper. Lifts provide easier accessibility but there are risks of breakdown. The Transport Reliability Report indicates that the Sydney Train lifts are available in 98% of time (ITSRR 2010). Accessible ticket counters, toilets, timetable and other amenities are considered important to the customer experience of wheelchair passengers. Table 1 presents a summary of wheelchair accessibility of 307 Sydney/NSW train stations, which indicates 134 stations, or 44% of all stations, are wheelchair accessible. All wheelchair accessible stations have step-free access to all platforms and essential station facilities. There are further 55 stations where only motorised wheelchairs may be accessible, but for manual wheelchairs, the help of a friend or carer is required.

Table 1: Wheelchair accessibility of Sydney train stations

Station amenities	Number of stations	% to total number of stations	Annual pax entries ('000)	% of total pax entries of all stations
All Sydney/NSW stations	307		292,510	
Wheelchair accessible	134	44%	238,060	81%
Wheelchair accessible with assistance	55	15%	11,265	4%
With a lift	114	37%	235,200	80%
With a ramp	148	48%	144,589	49%
With both lift and ramp	52	17%	125,180	43%
Wheelchair accessible toilet	132	43%	238,125	81%
Wheelchair accessible car space	142	46%	142,492	49%

Source: Station accessibility dataset collected from station attributes and amenities by Authors (2017)

Stations with high passenger entries and exits have been prioritised for providing wheelchair accessible facilities. Table 1 indicates that, in 134 wheelchair accessible stations out of 307 stations in Sydney (or 44% of total stations), the number of passenger entries accounts for 81% of total station entries. However, in 55 assisted accessible stations, the passenger entries only account for 4%[1].

1.3 Literature review

[1] Omitting transfer stations featuring two or more interchanging lines.

A literature review on evaluating accessibility and travel cost and effort of public transport for people with disabilities has been undertaken to give insights to how disability travels should be evaluated. Two conclusions that can be drawn from the review are:

- Traditional accessible facilities were considered for addressing a minority of the population (disabled people, mobility and vision impaired, etc.) and for complying statutory requirements. It has been recognised that accessible facilities can benefit ordinary people and public transport operators. Karekla et al. (2011) examined the benefits to people with disabilities, ordinary travellers and operators by elevating the platform to eliminate the vertical gap between platform and train for London Underground[2].
- More broadly, a concept known as “Universal Design” (UD) has been developed that refers to the requirements of public transport facilities in order to accommodate and increase the accessibility of as many passengers as possible. A stated preference study in Norway (Fearnley et al. 2011) suggested that the UD measures such as seating shelter, information at stops and on-board and station lighting, which benefit not only disable people but also ordinary passengers will provide a positive Net Present Value of the investment[3].

The literature review has pointed to the lack of understanding of travel barriers, difficulties and additional effort for disabled people using public transport. This will be the focus of this paper by comparing the generalised travel cost of wheelchair and other passengers for making rail trips.

2. Demands for rail trips by wheelchair passengers

The survey of disability, ageing and carers by Australian Bureau of Statistics (ABS 2009) shows that 18.5% Australian population has some sort of disability. Among them, 14.4% have core activity limitations who can be further divided into 4 levels: profound, severe, moderate and mild. These people cannot use all forms of public transport without experiencing some difficulty. Over one million people in NSW, and around 690 thousands estimated in Sydney, have core activity limitations. A proportion of them require a wheelchair when travelling outside their residence.

The ABS survey indicates that 82% of people with a profound or severe disability could use public transport, but only 7% of disability trips were made by public transport (bus, rail or ferry). There is a latent demand for disability travels if the public transport can provide proper and easy disability accessibility. Most frequently cited difficulties in using public transport by people with a mobility disability are access to stations, steps, doors, crowding, lack of space, access to toilets, lack of seats and standing spaces and issues associated with cognitive, behaviour and vision impairments.

Physical Disability Council of NSW (1998) estimated that 80,000 wheelchair users live in Australia, or about 0.41% of population. More recently, the data from disability survey (ABS 2009) shows 52,500 wheelchair users living in NSW, from which we have estimated that around 33,100 wheelchair users live in Sydney. The majority of them (89%) use manual wheelchairs and the remaining 11% use electric wheelchairs.

Historically, the patronage data of wheelchair users in Sydney train network is not collected. Data collected in an observation study at 12 Sydney Train stations conducted in 2009 (see Douglas 2011) shows 0.05% of station entries (i.e. 1 out of 2000 rail passengers) were

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[2] It can be argued that optimising stations for wheelchair accessibility may cause disbenefits for non-wheelchair users passengers, due to longer ramps than desired, preference for lifts over escalators, etc.

[3] Subject to the choice of parameters for the monetization of benefits, the results may diverge significantly

wheelchair passengers on stations with lift facilities, and there were no wheelchair passengers on stations without a lift facility. Using station entry / exit statistics, it has been estimated that 119,030 wheelchair trips have been made in Sydney train network per annum. On average, each wheelchair user in Sydney makes 3.6 return trips per annum, compared with 65 trips per capita per year for all Sydneysiders. Wheelchair users make either less rail trips, or less mobile, or both. Potentially, wheelchair users would use Sydney train services more frequently if disability accessibility had been improved.

3. Measuring rail trip accessibility from a whole journey perspective

The accessible stations must have accessible pathways allowing wheelchairs to reach essential amenities (ticketing counter, toilet and disability car space) and facilities for vertical movement (lifts and ramps) allowing wheelchairs to get to the concourse and all platforms in a station and to board or alight from trains. A train journey for wheelchair passengers is much more demanding than a similar journey made by other passengers, when all trip legs are considered. Table 2 compares the differences of a wheelchair train trip and a same trip made by other passengers to emphasise the extra efforts of wheelchair passengers in making such a trip.

Table 2: Compare a wheelchair trip with a same trip by other passengers

Trip leg	Wheelchair passenger	Other passenger
Access trip leg	• Park & ride used less	• Four modes are available: walk, kiss & ride, park & ride and bus
	• The speed of wheelchair ride is slower than walking, around 0.43 m/s • For motorised wheelchairs, it involves wheelchair running cost • For manual wheelchairs, greater effort is involved in riding a wheelchair	• Walk speed is relatively faster. On average, walking speed is around 1.1 m/s
	• Only 35% of Sydney Metro Buses are wheelchair accessible, makes bus an unreliable mode for access trips(1)	• Bus is used for access trips
Station / interchanges	• Not all station entrances are wheelchair accessible • A longer distance for accessing platforms by wheelchair pathways than walking distance by other passengers	• Usually multi entrance points to a station around station precinct
	• For vertical movement, wheelchairs can only use lifts and ramps • Assistance may be required for use of ramps by non-motorised wheelchairs	• Other passengers can use stairs, lifts, ramps and escalators • Only around 4% other passengers use lifts if both lifts and stairs are available(2)
	• Escalators are not wheelchair accessible	• Escalators are main modes for vertical movements in underground stations
On board	• A boarding ramp is used for	• Pay full price, some people are

	wheelchair boarding. Assistance from station staff is required • Pay half price or free if eligible for a travel pass • External crowding cost: space required for 1 wheelchair is 3 times greater of other passenger's	entitled to a concession
Egress trip leg	• Wheelchair riding is the main egress mode • Only 35% Sydney metro buses are wheelchair accessible, making bus an unreliable mode for egress trips	• Kiss & ride and park & ride are usually not available for egress trip leg • Walk or bus are main egress modes

Sources: (1) London Underground (2009); (2) NSW Government's Submission to the Five Year Review of the Disability Standards for Accessible Public Transport; (3) Douglas (2011)

- Table 2 highlights the inconveniences facing a wheelchair passenger in making a rail journey. For access trip, wheelchair passengers have to rely on someone to drive them to stations, or they have to ride wheelchairs themselves, which is usually slower, requiring a greater effort and involving a wheelchair operating cost in terms of electricity and repairing, etc.
- At stations / interchanges, wheelchair accessible pathways are usually longer compared with walking distance of other passengers. Lift is the main mode for vertical movement. There is a possibility of lift breakdown. A study undertaken by RailCorp[4] in the period from May 2010 to April 2011 of the sample of 2,721 station lifts shows that the lift availability was 98.5%. (At any time point, 98.5% lifts are working). The mean downtime of all lift breakdowns were 13.3 hours but the median downtime was only 2.6 hours. Some lift breakdowns may take up to 70 days to fix.
- To board to and alight from the train, assistance from station staff is required for using the manually deployed boarding ramps. On board, wheelchair takes a larger space than other passenger's.

3.1 Use the generalised cost of whole train journey as a relative measure of wheelchair accessibility

The generalised cost approach has been widely used in transport planning and mode choice analysis, as it can capture the monetary costs as well as other effects including travel time, transfer penalty, crowding and comfort, security and effort. In most empirical studies, the effects of crowding, transfer and security are derived from stated preference studies and expressed as additional equivalent on-board train time (Douglas Economics 2008). The effect of comfort and effort are expressed as equivalent travel time multipliers. The travel time is then monetised by the Value of Travel Time.

In this paper, the generalised travel cost is used to compare a typical rail journey by wheelchair and other passengers. It aims to use one measurable / quantifiable term to compare the difference of a rail journey by wheelchair and other passengers. The generalised travel cost is defined as:

$$\begin{aligned} Generalised\ cost &= \sum_{i=1}^{n}(T_i \times W_i) \times VTT + F|Concession + TR \times VTT + \sum_{i=1}^{n}(D_i \times WOC) \\ &+ (VOC + PC)|P\ \&\ R + (VOC + DriverT \times VTT)|K\ \&\ R \qquad (1) \end{aligned}$$

Where:

[4] Based on an internal communication.

i represents the travel leg breakdown of a train journey, typically include access, vertical travel on stairs, lifts, escalators and/or ramps, concourse walk, platform waiting, on-board train time and egress.

T_i represents the travel time spent at each travel leg. The breakdown from whole journey into different travel legs is based on level of travel effort for wheelchair and other passengers

W_i represents the weighting of travel effort / difficulty of different travel legs (Table 4).

VTT is the value of travel time savings, which is $15.41 per person hour as recommended by Transport for *NSW's Principles and Guidelines of Economic Appraisal of Transport Investment and Initiatives* (TfNSW 2013), indexed to 2017 by means of ABS's online Consumer Price Index Inflation Calculator[5].

F is the train fare price. It is noted that most wheelchair passengers are entitled to a concession price.

TR is the transfer penalty expressed as the equivalent on-board train time. The transfer penalty is assumed at 10 minutes of on-board train time per change platform transfer and 2 minutes for cross platform transfer (Douglas Economic 2008, TfNSW 2013).

WOC is the wheelchair operating cost per kilometre travelled which is estimated in Table 5.

D is the wheelchair riding distance (km) on access, egress, concourse and platform.

VOC represents the vehicle operating cost conditional to Park & Ride (P&R) and Kiss & Ride (K&R) access / egress mode.

PC represents the parking cost of Park & Ride mode. Most commuter car parking or on-street parking is free but some do involve a parking cost.

DriverT represents the driver's travel time for Kiss & Ride mode. If the purpose is specifically for dropping passengers, driver's time to and from stations should be included. For other purposes, only additional travel time attributable to passengers dropping should be included.

To quantify the generalised travel costs, a 'synthetic trip' is defined as shown in Table 3 where all trip details are specified. The synthetic trip represents the 'average' trip of all rail trips in Sydney train profile. To make the generalised travel costs comparable, the synthetic trip profiles for wheelchair and other passengers are identical in terms of distance of access trip leg, station attributes, travel time distance of rail trip and distance of egress trip. It simulates two identical trips, with the same origin and same destination: one made by a wheelchair passenger and another by a non-wheelchair passenger. Even though the travel distance of the two trips is the same, the travel times would be different as walking and wheelchair riding speed differ. The general valuation framework is shown in Table 3 and illustrated in Figure 1.

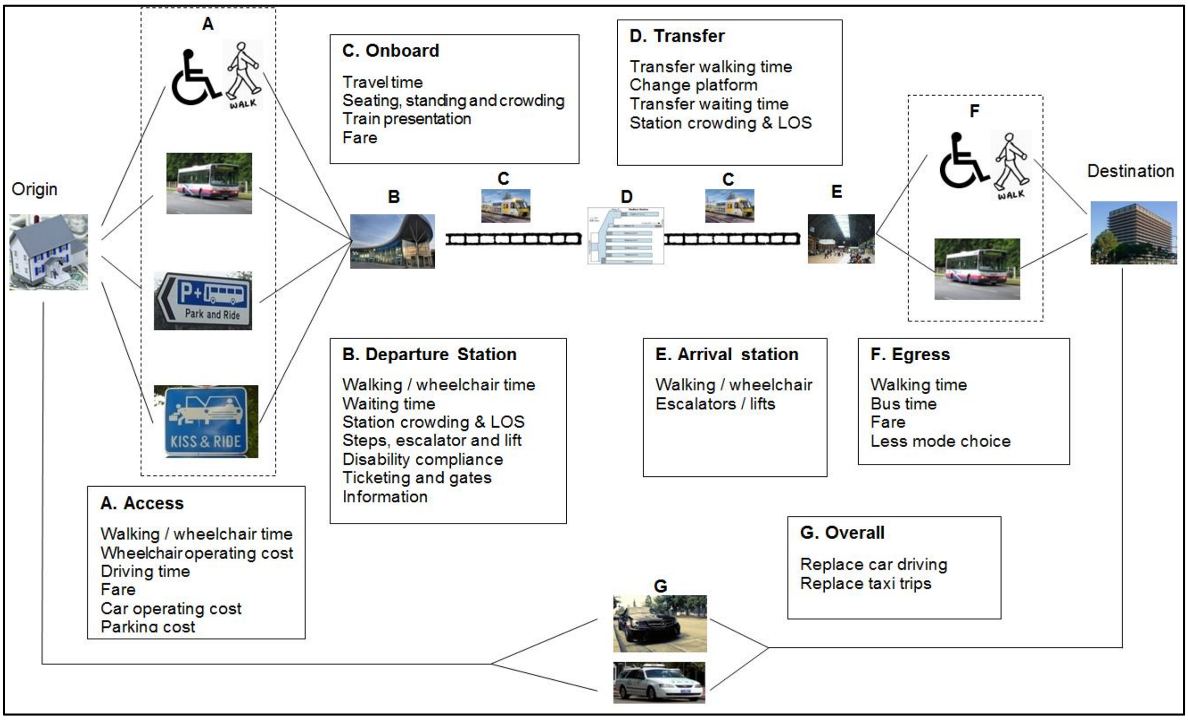
[5] http://www.abs.gov.au/websitedbs/d3310114.nsf/home/Consumer+Price+Index+Inflation+Calculator

Table 3: Synthetic trip profiles of wheelchair and other passengers

	Wheelchair passengers	Other passengers
Access trip leg	The weighted average of all access trips[1]: • Wheelchair ride: Mode share = 25%, distance = 0.7km • Kiss & Ride: Mode share = 70%, distance = 6 km • Bus: Mode share = 5%, bus distance = 5km, wheelchair distance = 0.5 km (to bus stop, and from bus stop to train station)	The weighted average of all access trips: • Walk: Mode share = 48%, distance = 0.7km • Kiss & Ride: Mode share = 20%, distance = 6 km • Park & Ride: Mode share = 16%, distance of drive = 7km, walk = 0.3km • Bus: Mode share = 16%, bus distance = 5km, walk distance = 0.5 km
Entrance station	An average suburb train station: • Lift ascending = 5m (vertical height) • Concourse / platform ride distance = 85m • Lift descending = 5m (vertical height) • Average platform waiting = 8 min[2] • Boarding: assisted required	An average suburb train station: • Stair ascending = 5 m • Concourse / platform walk distance = 70m • Escalator descending = 5 m • Platform waiting time = 8 min
On board	An average rail trip[3]: • Travel distance = 26 km • Travel time = 37 min • Ticket cost = $1.96 per trip (concession half price) • External crowding cost: take up to 3 persons' space	An average rail trip[3]: • Travel distance =26 km • Travel time = 37 min • Ticket cost = $3.93 per trip
Transfer	Likelihood of transfers and average transfer profile of Sydney stations: • Change platform transfer = 19%, transfer penalty = 10 min • Same platform transport = 7%, transfer penalty = 2 min • No transfer = 74% Average cross platform transfer: • Concourse / platform wheelchair = 80m • Lift ascending / descending = 5 m (vertical height)	Likelihood of transfers and average transfer profile of Sydney stations • Change platform transfer = 19%, transfer penalty = 10 min • Same platform transport = 7%, transfer penalty = 2 min • No transfer = 74% Average cross platform transfer: • Platform walk = 80m • Stair ascending = 5 m • Stair descending = 5 m
Egress station	Average profile of City station: • Lift ascending = 10 m • Concourse / platform wheelchair = 70 m • Alighting: assisted by station staff	Average profile of City station: • Escalator ascending = 10 m (vertical height) • Concourse / platform walk = 70 m
Egress trip leg	The weighted average of all egress trips: • Wheelchair ride share = 84%, distance=0.6km • Bus share = 16%, bus distance = 5km, then wheelchair distance = 0.3 km	The weighted average of all egress trips: • Walk share = 84%, distance=0.6km • Bus share = 16%, bus distance = 5km, then walk distance = 0.3 km

Sources: (1) TPDC (2006) Train Access and Egress Modes; (2) Estimated based BTS (2012) Compendium of Sydney Rail Travel Statistics. The proportion of AM peak trips = 33% of whole day trips. The proportion of PM trips = 32.7%. The proportion of off peak trips = 34.3%. Average headway in peaks = 16 minutes. Average headway in off peak = 27 minutes. Average platform waiting time = 0.72 * $\text{Headway}^{0.75}$, as recommended by ATC (2006). (3) Based on Douglas Economics (2008)

Figure 1: Framework for estimating generalised travel costs in a whole rail journey



Travel behaviour studies have consistently pointed out that passengers dislike waiting time and walking time. The travel time multipliers have been well established in the Economic Appraisal Guidelines in Transport for NSW. Douglas (2011) provided the multipliers for stairs, escalators and lifts based on UK studies. Table 4 presents the travel time multipliers based on existing literature. The use of these multipliers is straightforward. For example, the stair ascending multiplier of 4 means that 1 minute for climbing stairs up is equivalent 4 minutes of on-board train time.

Table 4: Travel effort multipliers

Travel legs	Wheelchair passengers	Other passengers
Onboard train time (base)	1.0	1.0
Access / Egress		
Walk / wheelchair	1.8	1.5
Car (P&R, K&R)	1.0	1.0
Bus	1.2	1.2
Vertical movement		
Stair ascending	N/A	4
Stair descending	N/A	2.5
Ramp	2.2	2.0
Escalator	N/A	1.5
Lift	1.5	1.5
Concourse walking / wheelchair	1.8	1.5
Platform waiting	1.5	1.5
Transfer		
Transfer walking / wheelchair*	1.8	1.5
Transfer waiting	1.5	1.5

Source: TfNSW (2013) and Douglas (2011). Effort of wheelchair riding is assumed 20% higher than other passenger walking. Effort of on-board train time, bus time and waiting time is assumed the same for wheelchair and other passengers[6].

[6] This may be considered a simplification, as wheelchair users obviously travel seated whilst non-wheelchair passengers may have to stand in crowded carriages.

3.2 Wheelchair operating cost

For other passengers, walking does not involve any monetary cost, being instead linked to health benefit in many project evaluations especially for active transport initiatives. However, wheelchair use is not economical if estimated on a per-kilometre basis. A wheelchair user in UK kept running cost receipts for 13 years that provides a reliable wheelchair life cycle cost (Williamson 2013). A typical purchase price of an electric wheelchair is around $4,260. Wheelchair is replaced every 5 years for an average user, after that it can be disposed for around $160. The costs for spare, charger, battery accessories and depreciation would total around $1,630 as shown in Table 5.

Cooper et al. (2002) collected driving characteristics over a 5day period from 17 electric-powered wheelchair users in the communities of Pittsburgh, Pennsylvania and the National Veterans Wheelchair Games in San Antonio, Texas, USA, and found that average driving speed was 0.43 metre / second and average wheelchair distance was 2.5 km per day (or 913 km/year). From total annual wheelchair running cost and distance driven, it has been estimated that average wheelchair operating cost is $1.78 per wheelchair-kilometre.

Table 5: Typical wheelchair operating cost

Cost Items	Life cycle cost (over 5 yrs)	Cost Per Annum
Typical purchase price	$4,310(1)	
Depreciation	$4,183	$836
Spare / charger replacements	$1,302	$260
Battery replacement	$1,204	$240
Upholstery, arms, various worn/damaged parts	$1,170	$234
Battery charging costs	$386	$78
Total cost		$1,650
Wheelchair operating cost ($/KM)		$1.80

(1) Source: http://www.uk-wheelchairs.co.uk/electric-wheelchairs?p=3. Accessed on 14/05/2013, indexed to March 2017 using ABS's Consumer Price Index Inflation Calculator.

3.3 Evaluating the access trip leg

Any rail journeys will have other modes used for access to and egress from the rail. The mostly used access modes are walk, Kiss & Ride, Park & Ride and bus, as shown in Table 6. For other passengers, around half of access trips are made by walking - the favourite mode if the distance from the origin to entrance station is less than 800m. The train catchment area is around 3 km radius from station in which people is most likely use train for commuting. Kiss & Ride, Park & Ride and Bus are likely used for access trips for people who live up to 10 kilometres away from train stations. There is no data for mode share of wheelchair access trips. The mode shares of wheelchair passengers in Table 6 are assumed values based on observations of wheelchair access in Sydney stations.

Table 6: Mode share of rail station access

Wheelchair passengers			Other passengers		
Mode	**Share**	**Distance to stations (km)**	**Mode**	**Share**	**Distance to stations (km)**
Wheelchair riding	25%	Average 0.7 km	Walking	48%	Average 0.7 km
Kiss and ride	70%	Average 6 km driving to station	Kiss and ride	20%	Average 6 km driving to station
Park and ride			Park and ride	16%	Average 7 km for driving then 0.3 km walking
Bus	5%	Average 0.3 km wheelchair riding to bus stop, 5 km bus then 0.2 km riding to station	Bus	16%	Average 0.3 km walking to bus stop, 5 km bus then 0.2 km walking to station

Source: Other passenger access mode share is sourced from Transport and Population Data Centre (2006). There is no research on access model share by wheelchair passengers. Mode share of wheelchair passenger access trips in Table above was based on assumptions calibrated with observations in Sydney train stations.

The cost of rail access trip is provided in Table 7, showing that travel cost of wheelchair passengers is about the double of other passengers. In estimating access costs, following assumptions were made based on existing literature:

- Walking speed: Typical walking speed: 1.1m/s; Fast walking speed: 1.7m/s
- Wheelchair (non-motorised) riding speed: 0.43-0.58m/s
- Vehicle operating cost at $0.35/vkt (TfNSW 2013, indexed to 2017 using ABS's Consumer Price Index Inflation Calculator)
- For Kiss and Ride, 50% drivers are chauffeuring passengers thus their travel time and VOC to and from station should be valued. The remaining 50% drivers provide lifts to passengers (with their own trip purpose) thus their travel time and VOC to station are excluded
- Bus fare cost is estimated at $0.94 per bus trip for other passengers and $0.47 per trip for people with disabilities. MyMulti weekly is the assumed ticket type if the bus is used for the access trip, and 20% total MyMulti ticket cost is allocated to bus access trip, remaining 80% is allocated to rail and ferry.

Table 7: Typical wheelchair operating cost

Access modes	Walking	Park and Ride	Kiss and Ride	Bus	Weighted Average Cost
Other passengers					
Mode share (%)	48%	16%	20%	16%	
Distance: walking to bus stop (m)				300	
Distance: in-car or in-bus (m)		7000	6000	5000	
Distance: walking to station (m)	700	300		200	
Travel time: walking (min)	10.61	4.55		3.03	
Travel time: in-car or in-bus (min)		13	11	15	
Time cost: walking ($)	$4.13	$1.77		$1.18	
Time cost: in-vehicle ($)		$3.37	$2.85	$4.67	
Time cost: serving passenger ($)			$2.85		
Vehicle operating cost ($) (1)		$2.48	$4.25		
Bus fare ($) (2)				$0.94	
Total access cost ($)	$4.13	$7.63	$9.97	$6.80	$6.28
Wheelchair passengers					
Access modes	**Wheelchair riding**	**Park and Ride**	**Kiss and Ride**	**Bus**	**Weighted Average Cost**
Mode share (%)	25%		70%	5%	
Distance: walking to bus stop (m)				300	
Distance: in-car or in-bus (m)			6000	5000	
Distance: walking to station (m)	700			200	
Travel time: wheelchair riding (min)	27			19	
Travel time: in-car or in-bus (min)			11	15	
Time cost: walking ($)	$12.75			$9.11	
Time cost: in-vehicle ($)			$2.85	$4.67	
Time cost: serving passenger ($)			$4.28		
Vehicle operating cost ($)			$4.25		
Wheelchair operating cost	$1.26			$0.90	
Bus fare ($)				$0.47	
Total access cost ($)	$14.01		$11.40	$15.16	$12.24

Source: (1) TfNSW (2013) Principles and guidelines of economic appraisal of transport investment and initiatives. (2) NSW public transport revenue collected by Authors (2017)

3.4 Evaluating the cost at entrance stations

From the whole journey perspective, wheelchair accessibility is largely defined by station accessibility, which is determined by station lifts and ramps. When both stairs and lifts are available, it was observed that only 4% of passengers use lifts. A high percentage of these passengers are mobility challenged (Douglas 2011). The generalised cost at station covers travel time and effort for the following activities:

- Vertical movement by stairs, lifts, escalators or ramps;
- Walking / wheelchair riding on concourse and platform;
- Platform waiting time.

The travel cost of a vertical movement is estimated through the following equations:

Travel cost in vertical movement = Travel time x Travel effort x Value of travel time (2)

Table 8 presents the travel speed, effort, travel time and costs for a vertical movement of 5 metre in height via stairs, lifts, escalators or ramps. (A typical suburb on-ground station configuration usually requires ascending 5m to the concourse, walking through the concourse and ticket gates, and descending 5m to platforms). Escalators involve the lowest cost and ramps have the highest for other passengers. For wheelchair passengers, the only available options are lifts and ramps, where lifts involve a much lower cost.

Table 8: Estimate the average travel cost on vertical movement

	Wheelchair passengers				Other passengers			
	Speed (m/s)	Travel Time (s)	Effort (multiplier)	Travel Cost (Cent)	Speed (m/s)	Travel Time (s)	Effort (multiplier)	Travel Cost (Cent)
Stairs								
Ascending					0.68	14	4	22
Descending					0.77	12	2.5	12
Lift								
Ascending	1.3	19	1.5	11	1.3	19	1.5	11
Descending	1.3	19	1.5	11	1.3	19	1.5	11
Escalator								
Ascending					0.82	12	1.5	7
Descending					0.88	12	1.5	7
Ramp								
Ascending	0.39	117	2.4	113	0.99	51	2	41
Descending	0.47	113	2.4	109	1.21	41	2	33

Source: Travel speeds on stairs, lifts, escalators and ramps are adapted from Lee (2005), Fruin (1971) and Douglas (2011)

The travel time is estimated from average speed on stairs, lifts, escalators and ramps. For stairs, ramps and escalators, inclined speeds have been used which can be converted to vertical speed if the gradient is known. Ascending speed is slower than descending, as observed in empirical studies (Fujiyama and Tyler 2004, Fruin 1971).

Stairs are a critical path in multi-floor transport facilities for other passengers but are a barrier both for elderly people and people with disability. Research on pedestrian speed on stairs has been basically observational and has regarded pedestrians as a flow. Travel speed on stairs is affected by stair gradient and pedestrian characteristics. The gradient is determined from riser-height and tread-length of steps. The typical stair gradient is around 32 degrees ranging from 25 to 39 degrees.

Pedestrian characteristics are defined by age and gender in empirical studies. Knoblauch et al. (1996) observed that people aged 62-65 year or more walk more slowly than younger people. Walking speed of women tends to be slower than that of men (Fruin 1971). In some studies, a ‘leg power index’ or ‘leg extensor power’, defined as pedestrian leg power divided by body mass, has been used to predict the pedestrian’s ability to ascending or descending stairs. Fujiyama and Tyler (2004) conducted an experiment of pedestrian speed on stairs for two groups: an elderly group consisted of healthy men and women aged between 60 and 81 who could walk and ascend / descend stairs in their daily lives and an ordinary group aged between 26 and 60. Stair speed in Table 8 is adapted from Fujiyama and Tyler study. Lee (2005) found that free speeds on stairways are about 0.77 m/s and 0.68 m/s in the descending and the ascending direction respectively. Climbing up and descending steps requires higher effort than lifts and escalators.

Speeds on lifts are around 1.0 – 1.6 m/sec based on lift manufacturers’ specifications. Travel time on lifts is even more than on stairs and escalators, as it includes a 5 sec waiting time, another 5 sec of door closing time, and finally a 5 sec exiting time (based on assumptions in Douglas 2011). This partially explains why other passengers prefer stairs than lifts. Speeds on escalators are about 0.88 m/s and 0.82 m/s in the descending and ascending directions respectively (Lee 2005). Escalators give the shortest travel time for vertical movements thus is the preferred mode. Speeds on ramps are assumed 90% of walking speed in ascending direction and 110% in descending direction. As the gradient of ramps is usually around 1:10, a travel distance of 50m is needed to raise a vertical height of 5m. Thus, ramps are linked to longest travel time.

Table 9 presents the estimated generalised travel costs at the entrance station, indicating the cost for wheelchair passengers is 34% higher than other passengers. This is mainly caused by longer wheelchair riding time on concourse and platform. An examination of

Sydney train station layouts indicates that the wheelchair pathways from a street to platform are usually longer than walking pathways for other passengers. Other passengers usually have multi station entrances while those accessible to wheelchair passengers are fewer. In addition, the speed of wheelchair riding is slower than walking.

Table 9: Generalised travel costs at entrance station

Wheelchair passengers		Other passengers	
Cost elements	**Cost ($)**	**Cost elements**	**Cost ($)**
Lift ascending 5m	$0.11	Stair ascending 5m	$0.23
Concourse wheelchair ride 85m	$1.28	Concourse walk 70m	$0.40
Concourse wheelchair ride: wheelchair operating cost	$0.15		
Lift descending 5m	$0.11	Escalator descending 5m	$0.07
Platform waiting 8 min (1)	$2.07	Platform waiting 8 min	$2.07
Total cost: entrance station	**$3.77**	**Total cost: entrance station**	**$2.81**

Note (1) The average platform waiting time is estimated from the average headway of 15 minutes in peak hours and 30 minutes in off peak hours. The waiting time = 0.72 x Headway$^{0.75}$, based on ATC (2006).

3.5 Evaluating the on-board cost

Station staff assistance is required for boarding and alighting train for wheelchair passengers. The time spent by station staff is not included in the generalised cost considering it is a part of their duties anyway. Once on-board, travel time is the same for wheelchair passengers and other passengers. However, wheelchair passengers usually only pay half price. In additional, RailCorp rolling stock has flip seats for wheelchair passengers to use which is changed to ordinary seats when no wheelchair passenger is present. One wheelchair passenger will occupy 3 seats which may contribute to additional crowding in peak hours. The generalised costs during on-board travel are presented in Table 10.

Table 10: Generalised travel costs: on-board

	Wheelchair passengers	Other passengers
Travel time (min)	37	37
Value of travel time	$9.62	$9.62
Fare *	$1.96	$3.05
External crowding cost	$1.30	
Total	$12.88	$12.67

Average rail fare has been estimated number of trips by distance and ticket type. For wheelchair passengers, the fare is the half of adult fee of the weighted average of fee by single, return peak, return off-peak, weekly, quarterly, half-yearly and yearly ticket types. For other passengers, it is weighted average of full fee, half fare concession and school student free trips.

The external crowding cost caused by larger size of wheelchair has been estimated using the train crowding cost model developed by Wang and Legaspi (2012), which simulates passengers' seating and standing for 581 train services in 3.5 AM peak and 3.5 PM peak periods in 12 Sydney train lines. In this paper, we have used the passenger capacity ratio of 120% or above as the threshold to determine if a wheelchair could contribute to additional crowding. At this passenger capacity ratio and above, a wheelchair would add crowding to standing passengers. The estimated crowding likelihood is 22.5% in AM peak hours, 17.1% in PM peak hours and no crowding in other off-peak hours. For an average trip of 37 minutes, the external crowding cost is estimated at $1.30for the whole journey.

3.6 Evaluating the transfer

Transfer can impose additional problem for wheelchairs, especially if the change platform is involved in that wheelchair passengers have to go through lifts and concourse. On average, 26% of rail trips involve a transfer. Among them, around 19% involved a change platform transfer (Douglas Economics 2008). For each change platform transfer, a walking distance of 150 metres, a transfer penalty of 10 minutes and an ascending and a descending through stairs or lifts are assumed. For the same platform transfer, only a transfer penalty of 2 minutes is assumed and the walking distance is negligible. Overall, the generalised cost for transfer for an average trip is $1.15 for wheelchair passengers and $0.77 for other passengers as shown in Table 11.

Table 11: Valuation of transfer for an average trip

	Wheelchair passengers	Other passengers
Change platform transfer	19%	19%
Transfer penalty (min)	10	10
Walking / wheelchair distance (m)	150	150
Walking / wheelchair travel time (min)	5.84	2.27
Travel time cost ($)	$5.33	$3.48
Wheelchair operating cost ($)	$0.26	
Costs for using stairs / lifts	$0.24	$0.37
Cost per cross platform transfer	*$5.84*	*$3.85*
Same platform transfer	7%	7%
Transfer penalty (min)	2	2
Cost per same platform transfer	*$0.51*	*$0.51*
No transfer	74%	74%
Transfer cost for an average trip	$1.15	$0.77

3.7 Evaluating the cost at exit station

The generalised costs at the exit station are estimated in the same approach as the entrance station. The difference is that there is no platform waiting time at an exit station. The exit station is assumed as an underground station in Sydney CBD where longer escalators are used by other passengers and wheelchair passengers are assumed using lifts. The estimated generalised travel costs are presented in Table 12.

Table 12: Generalised travel costs at exit station

Wheelchair passengers		**Other passengers**	
Cost elements	**Cost ($)**	**Cost elements**	**Cost ($)**
Lift up 10m	$0.15	Escalator up 10m	$0.16
Concourse wheelchair 80m	$1.27	Concourse walk 70m	$0.40
Wheelchair operating cost	$0.12		
Total cost at exist station	$1.54	Total Cost	$0.56

3.8 Evaluating the egress trip leg

In the egress trip leg, car options, either Park & Ride or Kiss & Ride modes, are generally no longer available. Passengers usually choose to walk if the distance from the station to destination is less than 1.0 km, or catch bus to get their destinations. Considering the egress distance is the same for wheelchair and other passengers, Table 13 presents the generalised travel costs in egress trip leg. MyMulti ticket types allow passengers to use them in different trips thus the ticket cost is not considered in egress trip (assuming the ticket fare has been captured in access trip leg).

Table 13: Generalised travel costs in egress trip

	Wheelchair passengers	Other passengers
Walk / wheelchair ride		
Mode share	84%	84%
Walk / wheelchair ride distance (m)	600	600
Travel time (min)	23	9
Travel time cost	$10.93	$3.54
Wheelchair operating cost ($/h)	$1.08	
Travel cost	$12.01	$3.54
Bus		
Mode share	16%	16%
Travel distance by bus (km)	5.00	5.00
Travel distance by walking (m)	300	300
Travel time by bus (min)	15	15
Travel time by walking (min)	12	5
Travel time cost	$10.14	$6.44
Wheelchair operating cost	$0.53	
Travel cost	$10.68	$6.44
Generalised travel cost for an average trip	**$11.80**	**$4.00**

4. Comparison with car and taxi trips

For a typical rail journey in Sydney train network with an average travel distance of 31 kilometres (access trip 3.6 km. train trip 26 km and egress trip 1.4 km), the generalised travel cost for wheelchair passengers is around 60% higher than other passengers, shown in Table 14. At each stage of travel, wheelchair passengers bear a higher cost. However, the cost difference was mainly caused in access and egress trip legs.

If a similar wheelchair trip is made by a car, a chauffeur is required which would need additional costs. Considering a moderate chauffeur labour cost of $32/h, vehicle operating cost and value of travel time cost for the passenger, the total cost for a similar trip would be around $60. NSW Government provides the Taxi Transport Subsidy Scheme (TTSS) for wheelchair users. Under the scheme, the qualified people with a disability (including wheelchair users) pay only a half of the total taxi charges but the maximum amount of subsidy is $32 per trip. For a similar trip made by taxi, the total taxi charge would be around $96. Thus, the wheelchair passenger would need to pay $63 and the Government subsidy of $32. The wheelchair passenger’s cost is around the same as driving a car by a chauffeur.

Wheelchair users prefer taxi although it is a more expensive mode. Table 15 indicates that, in a one-year period, a wheelchair person makes an average of 3.6 rail trips and 13.6 taxi trips, compared with other person making an average of 65 rail trips and 9.2 taxi trips.

Table 14: Summary of whole journey costs: wheelchair vs other passengers

	Wheelchair passengers	**Other passengers**
Access trip leg	$12.24	$6.28
Entrance station	$3.77	$2.81
On board	$12.88	$12.67
Transfer	$1.15	$0.77
Egress station	$1.54	$0.56
Egress trip leg	$11.80	**$4.00**
Total	**$43.38**	**$27.09**

Table 15: Trip rates made by rail and taxi

	Wheelchair passenger		Other people	
Mode	**Number of trips per year**	**Average number of trips per person per year**	**Number of trips per year**	**Average number of trips per person per year**
Rail trips	119,030	3.6	299,200,000 (2)	65.0
Taxi trips	451,667 (1)	13.6	42,340,000 (3)	9.2
Sydney population	33,100		4,605,992	

Source: (1) Estimated from NSW Taxi Transport Subsidy Scheme admin data. (2) Based on Compendium of Sydney Rail Travel Statistics 2012. (3) Based on 2010/11 Household Travel Survey summary report.

5. Dynamic pedestrian modelling for assessing travel cost

The use of dynamic pedestrian modelling can be very effective to assess the in-station section of a rail trip made by wheelchair users, i.e. the Entrance station considered in section 3.4 and the Egress station considered in 3.8.

The market offers a number of microsimulation modelling tools for representing passenger flows in stations. These tools are able to simulate certain aspects of human behaviour using computational algorithms which are calibrated according to observations and validated against genuine pedestrian movements in the attempt to replicate the dynamics of pedestrian movements, environment and activities encountered in real life venues.

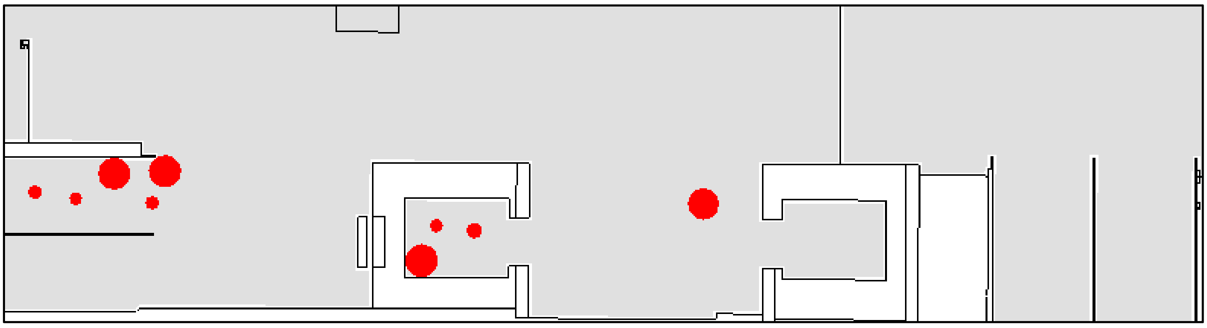
Typically, the algorithms used in these modelling tools are based on the on the principle of 'least effort' or ‘cost minimisation’, whereby agents move each next step in the direction that provides the best compromise between minimisation of walking distance and the possibility of keeping the preferred walking speed and having comfortable amount of space around (i.e. avoiding congestion), taking into account the agents’ preferences and objectives as well as the context, environment and other agents around.

Station environment can be simulated dynamically considering a vast range of parameters and observations. Station models validated against observed data can then be used to undertake simulations with predictive capacity across a range of scenarios and design options, returning qualitative and quantitative outputs, including, inter alia, the following:

- Journey time and related cost for each activity and entity type;
- Delays, distance walked;
- Analyse use and space occupation in lifts and vehicles.

Figure 2 provides a screenshot of a dynamic pedestrian modelling simulation in which wheelchair users (represented by the large red dots) users can be seen using lifts along with other passengers (represented by the small red dots).

Figure 2: Screenshot of a dynamic pedestrian modelling simulation showing wheelchair users



The use of dynamic simulations offers the possibility to calculate information regarding 'generalised journey time' (GJT), derived as the sum of the individual journey times within a station by applying different weightings to different activities to represent their undesirability.

For example, a pedestrian modelling tool such as Legion SpaceWorks can generate the following Journey Time and Generalised Journey Time reports:

- Detailed Journey Time Report: an entity-level report file providing details on in-station journey times for each model's agent, which makes it possible to identify, for example, the individual and general journey times for the wheelchair users included in the simulation;
- Detailed Generalised Journey Time Report: an entity-level report file providing details on in-station journey times for each model's agent, including individual time spent on each activity (walking, waiting, queuing, delayed, on stairs up, on stairs down, on escalator up, on escalator down, etc.);
- Summary JT, GJT and Social Cost Report: a summary report providing information on Journey Time, Generalised Journey Time and Social Cost based on a VOT parameter, arranged by entity activity, by entity type, and by Origin/Destination.

By combining the information from the reports above, it is possible to identify the journey times during in-station movements for each category of passengers, including wheelchair users and to automatically calculate the individual as well as generalised cost of the in-station section of the rail trip.

One possibility offered by dynamic modelling is to compare the performance of one design with different passenger composition (e.g. assuming a growth in the number of wheelchair users) or different design options with the same passenger demand. The interaction between wheelchair and non-wheelchair passenger, or the impact of changes to a station to improve accessibility is reflected in the walking times, densities, vertical travel etc. By comparing different scenarios and/or passenger composition, it is possible to assess the variations in the cost incurred by wheelchair and non-wheelchair passenger.

The appendix to this paper provides an example of generalised journey time and social cost from a typical pedestrian modelling tool.

6. Conclusions and further research

The detailed examination of the generalised trip cost reveals that travel time and effort involved in a rail trip for wheelchair passengers are much greater than other passengers. The parameters and methodologies developed in this paper for identifying the travel cost of wheelchair passengers will contribute to improve economic appraisal of public transport facilities for mobility accessibility and will provide insights for planning disability facilities in public transport network. The generalised travel cost of wheelchair passengers for a typical rail trip is around 60% higher than other passengers, but it is still less expensive than alternative modes implying rail patronage by people with a disability can increase if proper accessible facilities are provided. Currently, only 44% of Sydney train stations are wheelchair accessible. Further research is needed to understand the travel behaviour of wheelchair users in the catchment of stations that are not wheelchair accessible. Do they travel to next wheelchair accessible station or do they use car / taxi more? Currently, wheelchair boarding is often through a manually deployed boarding ramp requires station staff's assistance. The research on London Underground Platform and Train Interface (Karekla et al. 2011) indicates positive economic returns by building platform humps in a part of platform or by fully raising the whole platform to close the vertical and horizontal gaps between the platform and train. These improvements will benefit not only people with disabilities (by providing direct boarding and alighting for wheelchairs), but also other train users from incident reductions and operators from reduced staffing cost and running cost savings from the reduced boarding and alighting time. Further research is needed in this area. The last section of the paper provided a brief overview of how dynamic pedestrian modelling can be used to assess the cost of travel within a station (or a modelled area) for wheelchair users in great detail; the appendix to this paper provides an example of generalised journey time and social cost from a typical pedestrian modelling tool.

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Appendix - Example of generalised journey time and social cost summary report from dynamic pedestrian simulations

This appendix provides an example of generalised journey time and social cost from a typical pedestrian modelling simulation. Table 16 and Table 17 provide generalised journey time and social cost summary reports from a typical simulation of a suburban railway station, considering an AM peak-hour patronage scenario, with a population composed of different categories of passengers, each with different walking speeds, size and routing characteristics.

The reports in this example provide journey times and costs for each activity and for each typology of passenger, considering each individual agent included in the simulation. The results from the simulation consider each individual agent's movements from accessing the model area on the streets adjacent to the station until boarding the preferred train service, and vice versa. The station model includes lifts, stairways and ramp for vertical circulation; the cost for each activity is represented in Table 17.

Different Value of Time and weighting parameters can be used for each activity entailed in reaching the desired final destination (boarding a train or exiting the station building). A congestion factor can also be considered in the calculation of the total cost of journey, as it can be seen in Table 15 and Table16 overleaf.

Table 16: Example of a Generalised Journey Time and Social Cost summary report by Passenger Typology from a dynamic pedestrian simulation

Passenger Typology	Number entities	Journey Time	Generalised Journey Time	Congestion Factor	Journey Cost[1]	Congestion Cost[1]	Total Cost[1]	Annualised (250 days/year)[1]
		dd:hh:mm:ss	dd:hh:mm:ss	dd:hh:mm:ss				
Non-PRM	1093	1:22:38:59	5:03:38:25	0:00:06:50	$938.43	$0.87	$939.30	$234,824.21
Wheelchair users	255	0:22:12:37	2:05:28:43	0:00:21:29	$405.90	$2.72	$408.62	$102,155.94
Passengers with permanent or temporary physical mobility impairments	5	0:00:20:38	0:00:56:06	0:00:00:00	$7.10	$0.00	$7.10	$1,774.37
Non-disabled passengers with heavy luggage	23	0:01:04:33	0:02:46:52	0:00:00:05	$21.11	$0.01	$21.12	$5,280.34
Non-disabled passengers with large luggage	9	0:00:22:45	0:01:01:37	0:00:00:00	$7.80	$0.00	$7.80	$1,949.16
Adults with young children	2	0:00:06:06	0:00:15:39	0:00:00:00	$1.98	$0.00	$1.98	$495.09
TOTAL		2:22:45:40	7:14:07:25	0:00:28:26	$1,382.32	$3.60	$1,385.92	$346,479.11

1 Assuming Value of Time=$7.59/hour

Table 17: Example of a Generalised Journey Time and Social Cost summary report by Activity from a dynamic pedestrian simulation

Activity	Weighting	Journey Time	Global Journey Time	Congestion Factor	Journey Cost	Congestion Cost	Total Cost
Global: Walking	2.000 + 0.500 CF	17:46:59	1:11:33:58	0:00:02:42	$269.95	$0.34	$270.29
Global: Waiting	2.500 + 1.000 CF	0:17:40:35	1:20:11:28	0:00:04:14	$335.41	$0.54	$335.95
Global: Queuing	3.400	0:00:09:10	0:00:31:10	0:00:00:00	$3.94	$0.00	$3.94
Global: Delayed	2.500	0:01:35:40	0:03:59:10	0:00:00:00	$30.26	$0.00	$30.26
Global: On Stairs Up	4.000	0:10:40:52	1:18:43:28	0:00:00:00	$324.28	$0.00	$324.28
Global: On Stairs Down	2.500	0:00:39:45	0:01:39:24	0:00:00:00	$12.57	$0.00	$12.57
GJT Entire Station: Walking	2.000 + 0.500 CF	0:12:48:18	1:01:36:37	0:00:13:29	$194.38	$1.71	$196.09
GJT Entire Station: Waiting	2.500 + 1.000 CF	0:05:54:07	0:14:45:19	0:00:08:00	$111.99	$1.01	$113.01
GJT Entire Station: Queuing	3.400	0:00:01:00	0:00:03:26	0:00:00:00	$0.43	$0.00	$0.43
GJT Entire Station: Delayed	2.500	0:00:35:34	0:01:28:57	0:00:00:00	$11.25	$0.00	$11.25
GJT Entire Station: On Stairs Up	4.000	0:02:53:35	0:11:34:23	0:00:00:00	$87.84	$0.00	$87.84
TOTAL		2:22:45:40	7:14:07:25	0:00:28:26	$1,382.32	$3.60	$1,385.92