Issue 21(2), 2021, pp. 1-18
https://doi.org/10.18757/ejtir.2021.21.2.4794

TU Delft OPEN

EJTIR

ISSN: 1567-7141
http://ejtir.tudelft.nl/

Optimum Stop Spacing for Accessibility

Hao Wu[1]
School of Civil Engineering, University of Sydney, Australia.

David Levinson[2]
School of Civil Engineering, University of Sydney, Australia.

The cumulative opportunities measure accessibility is defined as the number of opportunities reachable under a given time threshold. The spacing between transit stations is fundamental for accessibility by transit, yet the stations cannot be easily relocated in built-up areas. This paper examines the relation between transit stop spacing and person-weighted accessibility for an urban train route through an analytical model, and identifies that for each type of transit (e.g., given some combination of vehicle acceleration, deceleration, top speed, dwell time, platform type), an optimal stop spacing exists that maximizes accessibility; neither short nor excessive stop spacing are efficient in providing accessibility. Rail is used as example, though the model and findings are applicable to bus services as well. This paper brings attention to the importance of stop spacing in accessibility, and provides guidelines for transit planning for the operational improvement of transit accessibility.

Keywords: *accessibility*, *stop spacing*, *transit.*

1. Introduction

Transit systems should be designed to increase access, enabling customers to easily reach destinations. The level of transit accessibility depends on both the transit infrastructure (e.g. stations) and service provision. While scheduled transit services can be modified regularly, the configuration of transit stations are more permanent and stations cannot be easily relocated. Hence, because of the long term fixity of the location of transit stops, getting that location right should be a conscious strategic planning decision by transit operators to improve accessibility.

Transit accessibility to jobs affects mode choice (Owen and Levinson, 2015, Wu et al.,2019a), transit patronage (Cervero et al., 2010, Wu et al., 2019b), property value (Debrezion et al., 2007, Mayor et al., 2012). and has economical impacts (Fernandez, 1994). While many other transit performance

[1] A: University of Sydney, Civil Engineering Building J05, NSW 2006, Australia E: h.wu@sydney.edu.au
[2] A: University of Sydney, Civil Engineering Building J05, NSW 2006, Australia E: david.levinson@sydney.edu.au

metrics, including the areal coverage, ridership, time headway, etc. are based on the transit operators' perspective, the transit access to jobs directly measures the experience of transit passengers, and it provides an easily quantifiable measure of how transit service can be improved.

In this paper, accessibility is defined using the cumulative opportunities measure, reflecting the number of opportunities reachable within a given travel time (Hansen, 1959, Ingram,1971, Wachs and Kumagai, 1973, Wickstrom, 1971).

The travel time, and thus the level of access is affected by the convenience of transfers between different routes, and transit systems in different cities have varying levels of complexity. We use the case of a single transit line to examine the discuss the implications of stop spacing on access, since the transfer locations can be viewed as destinations; this simplification also ensures that findings from the single-line setting to be easily understandable, and applies under any circumstances.

Foremost, faster systems require greater distance between stops. Greater distance between stops increases the costs of access to and egress from those stops. Among other factors, distance between transit stations affects the level of accessibility provided by urban trains, and has long lasting effect due to the semi-permanent nature of rail infrastructure. Operational differences between various types of urban rail technologies (Metro, light rail, tram, etc.) including vehicle acceleration and deceleration characteristics, cruising speed, station dwelling potentially affect the level of accessibility achievable; these factors are investigated in this study.

Though transit systems often improve accessibility, and choices of investment by private firms and approved by government have been shown to favor those which expand access (Levinson et al., 2016), maximizing accessibility is usually not the explicit objective of public transport agencies, nor is it often a quantified consideration when routes and stations are planned (Boisjoly and El-Geneidy, 2017). There is a lack of motivation in improving transit accessibility by transit operators, who often cannot directly capture the value access generates, and the role of stop spacing in transit accessibility is often not recognized. Transit agencies operate under tight budget constraints, with two main objectives to improve coverage, and to increase ridership (Walker, 2012). The transit coverage issue stems from the limited area covered by each transit stop, and requires more stops with fewer coverage over-laps to increase overall coverage along the route (and to contain operating cost) (Ibeas et al.,2010, Saka, 2001); the ridership issue requires more densely spaced stations and coverage overlaps to capture more passengers along the planned route. Transit systems with similar capital investments can produce different levels of accessibility depending on their modal and spatial configuration (Ermagun et al., 2015), which affects transit mode share (Owenand Levinson, 2015) and patronage. Coverage and ridership goals affect stop spacing; how transit accessibility can be affected will be investigated.

While this paper focuses on accessibility and its relation to stop spacing, the importance of transit planning has been acknowledged by other articles. Tirachini et al. (2010) implicitly examines accessibility by comparing the operator and user costs from different transit planning scenarios. The trade-off between more transit stops and increased time penalty is acknowledged by Ceder et al. (2015). Van Nes and Stolk (2012) examines the accessibility of railway stations with space syntax. The stop location minimizing total cost is discussed by Wirasinghe and Ghoneim (1981) and Alonso et al. (2011), in which Alonso et al. (2011) examine stop location under congestion and elastic demand. Ibeas et al. (2010) proposed a model to minimize total social cost of public transport by varying stop spacing. dell'Olio et al.(2006) proposed a mathematical programming model to study frequency and stop locations to minimize operating cost of the transit system. Saka (2001) proposed an analytical model based on passenger demand, bus acceleration, deceleration characteristics, cruise speeds, etc.to study the optimum bus stop spacing for reducing required fleet size.

Transit route design and stop spacing often face a lack of objectives. Based on the transit users' perspective, travel time is often used as a performance measure for the quality of route design (Kikuchi and Vuchic, 1982, van Nes and Bovy, 2000). However, such travel time objectives rely heavily on complex behavioral assumptions on trip destinations. On the other hand, accessibility measure provides an intuitive and practical performance objective for transit stop spacing, using one simple assumption on the traveler's travel time budget.

This paper argues for the existence of an optimum stop spacing for accessibility, and illustrates through an analytical model how this optimum spacing associates with operational characteristics of transit services. The paper provides general accessibility guidelines for the planning of transit systems, and discusses the effectiveness of operational improvement measures for better accessibility.

2. The analytical model

2.1 Accessibility measure

The accessibility to jobs measured by the analytical model is the number of job opportunities encapsulated by all possible paths of a one-way transit trip within a travel time threshold of 30minutes; the accessibility model is formulated as in Equation 1 and Equation 2. Opportunities covered within that 30-minute one-way travel time threshold are considered reachable. We use job locations to represent opportunities, since access to jobs is often used as a surrogate for work opportunities, services, and amenities (Giuliano et al., 2010, Owen and Levinson,2015). The 30-minute threshold reflects the common one-way commute travel time in large cities which has held stable over time (El-Geneidy and Levinson, 2006, Marchetti, 1994). The accessibility measures tend to be correlated across other time-thresholds and between cumulative opportunities and gravity measures, so we don't think other metrics would affect the insights of the analysis.

$$A_i = \sum_{j=1}^{n} O_j \, . f(C_{ij}) \tag{1}$$

$$f(C_{ij}) = \begin{cases} 1 \; if \; C_{ij} < B \\ 0 \; if \; C_{ij} \geq B \end{cases} \tag{2}$$

A_i: cumulative accessibility for an average individual within service area of station i

O_j: number of opportunities at location j

$f(C_{ij})$: travel impedance as a function of travel time from i to j, C_{ij}

A_i: travel time budget (30 minutes assumed by the model)

2.2 Spatial distribution of jobs and transit riders

The model assumes the number of transit riders and job opportunities decrease with distance from the station. The assumption on the spatial distribution of jobs sets the amount of opportunities that exist within the 30-minute catchment area; the distribution of transit riders affects the person-weighted station access time. Spatial distribution of jobs and transit riders are represented by densities ($jobs/m^2$ and $riders/m^2$); as an illustration, the model assumes $30{,}000/km^2$ for both jobs and riders. The density of jobs decrease linearly away from transit stations; the population density is assumed to be uniform, but the percentage of population using transit (transit riders) decreases linearly with distance to transit stations. For simplicity, the model assumes identical density of jobs and transit riders with zero distance to transit stations; both job and rider densities decrease at the same rate (k), as a function of distance from transit stations (d). This type of distribution assumption is elegant in that it does not require extra parameters Daganzo (2010).

The percentage of transit users from outside the service area is low (McNeil et al., 2017). By limiting station service area with a walking distance of L, the model assumes when the distance to the closest station (d) reaches the limit of service area (L), the density of both job opportunities and the density of transit riders (ρ_d) drop to zero (Equation 3).

$$\rho_d = \rho(1 - \frac{d}{L}) \tag{3}$$

ρ_d: density of transit riders or jobs with a distance of d to the nearest transit stop

ρ: density of riders or jobs with zero distance to transit stop

d: distance to the nearest transit stop (Manhattan distance)

L: walking distance defining service area of a transit station

It is worth noting that the survival function calibrated for walking distances (Iacono et al.,2008) is very close to linear for most of its range.

2.3 Pedestrian network

The model assumes a grid type pedestrian network, so walking distance for station access and egress uses the Manhattan distance. Figure 1 shows the rectangular shape of coverage area provided by each of the transit stop (stops in red dots). Size of the coverage area depends on the willingness to walk. An 800-meter (half-mile) walking distance threshold is used for the coverage areas (McNeil et al., 2017). Individuals vary in physical stamina, and willingness to walk long distances; a 400-meter walking distance threshold is usually considered acceptable for buses (Walker, 2012), although people are willing to walk longer to access express transit services such as the urban rail (Guerra et al., 2012)

Stop spacing affects the coverage area by each stop, as well as station access time, and opportunities reachable during egressing from the destination stop. When spacing between stops decreases, overlapping coverage areas begin to form in between stations (blue areas in Figure 1), reducing station access distance; at the destination end, the number of opportunities covered per transit stop decreases with denser stop spacing.

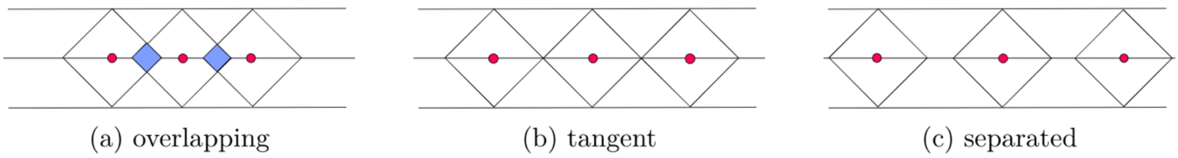

Figure 1. Station service areas using Manhattan Distance; red dots represent transit station; overlapping coverage areas shown in blue.

2.4 Components of travel time

The model uses a 30-minute travel time threshold for clarity. The analytical model defines a one-way transit trip as first accessing the closest transit stop (which may involve out-of-direction travel), on-board travel, and egressing from the terminal transit stop to the actual destination.

The travel time for each one-way transit trip includes station access, egress, on-board travel time and waiting time on the platform. Transfers are ignored, as the concept presented here is the same for transfers except that the 'actual destination' is instead replaced by the transfer location. Theoretically, time spent waiting on the platform can be eliminated if passengers can time their departures according to the transit timetable, and if trains strictly run on schedule. The waiting time is further complicated by individual variations and transit timetable reliability issues; such behavioral aspects of waiting time introduces unnecessary complications, thus the waiting time on platform is set to null, assuming the travelers have knowledge of the timetable and would react rationally. The waiting time com-ponent is therefore excluded from this analysis. A one-way travel time C_{ij} can be expressed as Equation 4.

$$C_{ij} = T_a + T_o + T_e \tag{4}$$

C_{ij}: one-way travel time

T_a: station access time

T_o: on-board travel time

T_e: station egress time

For a morning commute, the station access time (T_a) is the time spent walking from the residence (trip origin) to the closest transit station. For the access time to be representative, it is calculated as the population-weighted average walking time to station for transit riders within the coverage area of the origin transit station (Figure 1). Station access time is calculated with Equation 5, its derivation is provided in Appendix; Table 1 provides a list of variables used in this study. Station access time is affected by the spacing between stations. When stations are spread wide apart to the extent there are no overlapping coverage areas, station access time is at its maximum. As the spacing between stations shrink and overlapping coverage areas begin to occur (shown in Figure 1), the person-weighted walking distance is reduced. The extent of access time reduction relates to how closely the stops are placed.

$$T_a = \begin{cases} \frac{L}{2 \cdot V_w} & if\ D_s \geq 2L \\ \frac{D_S^3 - 4LD_S^3 + 16L^3}{(4D_S^3 - 24LD_s + 48L^2) \cdot v_w} & if\ D_s < 2L \end{cases} \quad (5)$$

Table 1. Variables and Abbreviations

C_{ij}	One-way travel time from station i and job j	L	Walking distance defining station service area (m)
A_i	Cumulative accessibility for an average individual within service are of station i	k	Rate of density decay, $k = \rho/\text{L}$
D	Travel distance on rail track	D_s	Distance between stops (m)
T_a	Station access time	ρ	Population/Job density with zero distance to station (per m^2)
T_e	Station egress time	B	One-way trip travel time budget
T_o	On-board travel time (Total)	ρ_d	Population/Job density with a distance of d to station
t_{o1}	On-board acceleration time	v_w	Walking speed (m/s)
t_{o2}	On-board cruising time (at top speed)	v	Train top running (cruising) speed
t_{o3}	On-board deceleration time	v_o	Train operating speed, including station stops
t_{o4}	On-board station dwell time	a	Rate of train acceleration
N_s	Number of stops on rail track with distance D and stop spacing D_s	b	Rate of train deceleration
P_c	Total population covered by a single transit station	d_c	Total station access distance by transit riders within a single transit station

The on-board travel time between two stations (T_o) depends on the distance between the origin and destination stop, vehicle operating speed, acceleration and deceleration characteristics of the train, the number of stops in between, and the dwell time the vehicle will spend boarding and alighting passengers for every stop it makes (National Academies of Sciences, Engineering, and Medicine, 2013). As a train travels between stations, it inevitably goes through the cycle of decelerating from its top running speed, come to a complete stop for passengers to board and alight, then accelerate back to the cruising speed again (National Academies of Sciences, Engineering, and Medicine, 2013). This speed cycle is necessary for passengers to utilize the transit system, however, all passengers already on-board incur extra time with each stop added to the route. Take two extreme cases for example: if a train does not make any stop during its one-way run to its destination, then the aggregated travel speed will almost be the same as the top operating speed; and if the train is making stops all the time, it will be excessively slow as it has to start decelerating as soon as it clears the previous stop.

The overall travel speed of the train will always be below the top running speed, and the more stops the train makes, the lower its operation speed becomes. The on-board travel time has four components: acceleration (t_{o1}), deceleration time (t_{o2}), time the train runs at top running (cruising) speed (t_{o3}), and dwell time serving passengers on platforms (t_{04}) (shown by Equation 6). Stations with larger demand will usually have longer dwell time to serve passengers; an additional operating margin (buffer time) is usually added in addition to the dwell time to absorb service disruptions and improve timetable robustness (National Academies of Sciences, Engineering, and Medicine, 2013). The length of buffer time largely depends on the transit operator; we assume a default 45 seconds dwell time for all stops, including buffer time.

$$T_o = \sum t_{o1} + \sum t_{o2} + \sum t_{o3} + \sum t_{o4} \qquad (6)$$

Time remaining from the travel time budget after arriving at the terminal stop (station egress time T_e) is used for reaching opportunities through walking. Opportunities within this walking catchment area are considered accessible. When stops are densely spaced, the number of opportunities assigned to each stop decreases. It can be observed that without the explicit intention to optimize for accessibility, different types of transit have different stop spacing configurations: metro and heavy rails tend to have longer stop spacing, streetcars and trams with lower speeds have stops located much closer together. Such arrangement in stop spacing improves accessibility, which will be discussed in the following sections.

2.5 Operating speed

Assuming there exists an optimum stop spacing for accessibility (i.e. non-monotonic relation between stop spacing and accessibility), it follows that the same level of accessibility (other than the peak accessibility) can be borne by two different stop spacing distances. Stop spacing affects both the number of opportunities reachable (accessibility), and the distance traveled on rail track in the same time frame. Operating speed measures how fast a train travels on its route, including station stops (National Academies of Sciences, Engineering, and Medicine, 2013). Under the same travel time budget, higher operating speeds enable passengers to travel further down the route in the same travel time. Although this higher operating speed doesn't necessarily add to the person-weighted accessibility, it affects the spatial distribution of accessible opportunities.

The operating speed is sensitive to the same set of parameters as the level of accessibility, including the rate of acceleration and deceleration (e.g. power-to-weight ratio and braking system), terrain gradient, dwell time, and stop spacing (National Academies of Sciences, Engineering, and Medicine, 2013). Improvements in those parameters increases operating speed, and thus distance reachable by transit users. Stop spacing is the most important consideration among the parameters, since stations are semi-permanent structures that can- not be easily relocated, yet their spacing have major ramifications for both accessibility and operating speed.

We explore analytically how the operating speed is affected by stop spacing. For a typical configuration, a default top running (cruising) speed of 60 km/h is set for the train; the rate of acceleration (a) and deceleration (b) are both set at 1.3 m/s^2, and each dwell time cost 45 seconds, per the Transit Capacity and Quality of Service Manual (National Academies of Sciences, Engineering, and Medicine, 2013). Equation 7 describes operating speed as a function of stop spacing; the derivation is shown in appendix.

$$\mathrm{v_o} = \frac{\mathrm{D}}{\mathrm{t_o}} = \frac{\mathrm{v \cdot D_s}}{\mathrm{v^2}\left(\frac{1}{2\mathrm{a}}+\frac{1}{2\mathrm{b}}\right)+\mathrm{v \cdot t_{o4}}+\mathrm{D_s}} \qquad (7)$$

3. Results and discussion

Stop spacing has a fundamental effect on accessibility, both short and excessive stop spacing are inefficient in delivering accessibility. Excessive stop spacing allocates long stretches of travel time en route without making stops, this point-to-point transit service generates very limited access to the land along the rail track. Reducing stop spacing causes chunks of stop coverage areas to overlap, it follows that diminishing marginal gains in accessibility per stop combines with accumulated time penalties by each additional stop will gradually reduce the value of increasing stop density. A critical point will be reached where the value of additional stop density is about to turn from positive to negative. The optimum stop spacing is reached at that point.

The degree of optimum accessibility reachable, as well as the stop spacing by which this optimum is reached depends on the system hardware (vehicles' rate of acceleration, deceleration, top running speed), and operational details (door type, bike carry policies, etc.). Improvements in system hardware and in operations has varying impact on the subsequent accessibility, and carry different costs to transit operators. This section discusses the sensitivity of accessibility to these system parameters, and feasibility of implementing these changes.

3.1 Top running speed

The top running speed is the terminal, or cruising speed a train reaches after serving passengers and accelerating at a constant rate from the previous station. With very close stop spacing, the top running speed may not be reached before reaching the next station. Figure 2 plots the relation between top running speed, stop spacing and the person-weighted accessibility, using 45 seconds default dwell time.

Accessibility increases with higher running speed at each stop spacing distance. Initial improvement in speed produces proportionally greater increase in accessibility; raising speed for services that already have considerable running speed has less effect on accessibility, so there is a diminishing marginal return to increasing speed. The transit system incurs infrastructure and maintenance cost for increasing speed; passenger throughput can be negatively impacted as higher speed requires longer time-headway separation between services (National Academies of Sciences, Engineering, and Medicine, 2013). Thus a balanced speed for accessibility can be considered in practice. The level of accessibility provided by a streetcar-type transit with 30 km/h top speed falls far behind that of a 50 km/h service at every stop spacing.

Higher speed services generally require longer stop spacing to maximize accessibility. This has been operationalized, perhaps unintentionally, by many transit services; high speed rail, metro and BRT generally have separate right-of-way and have stations placed further apart than tram and streetcars in mixed traffic. For streetcars and trams (mostly in downtown or CBD), it become desirable to allow higher station density to improve accessibility. For rails with moderate speeds (60-70 km/h top speed), optimum stop spacing is slightly short of the coverage radius, so there is some overlapping coverage area both for station access and egress; slower services require more service overlaps to optimize for accessibility.

Municipal decision makers need to be conscious of stop spacing issue and the resulting accessibility provided by services with different speeds for the choice of transit investment. Low speed transit services in mixed traffic are inherently disadvantaged in providing accessibility. Civil speed limits are imposed upon trains where there are curves and steep downgrades (National Academies of Sciences, Engineering, and Medicine, 2013), which implies that cities with unfavorable terrains and circuitous routes might be inhibited in their ability to provide accessibility through public transport.

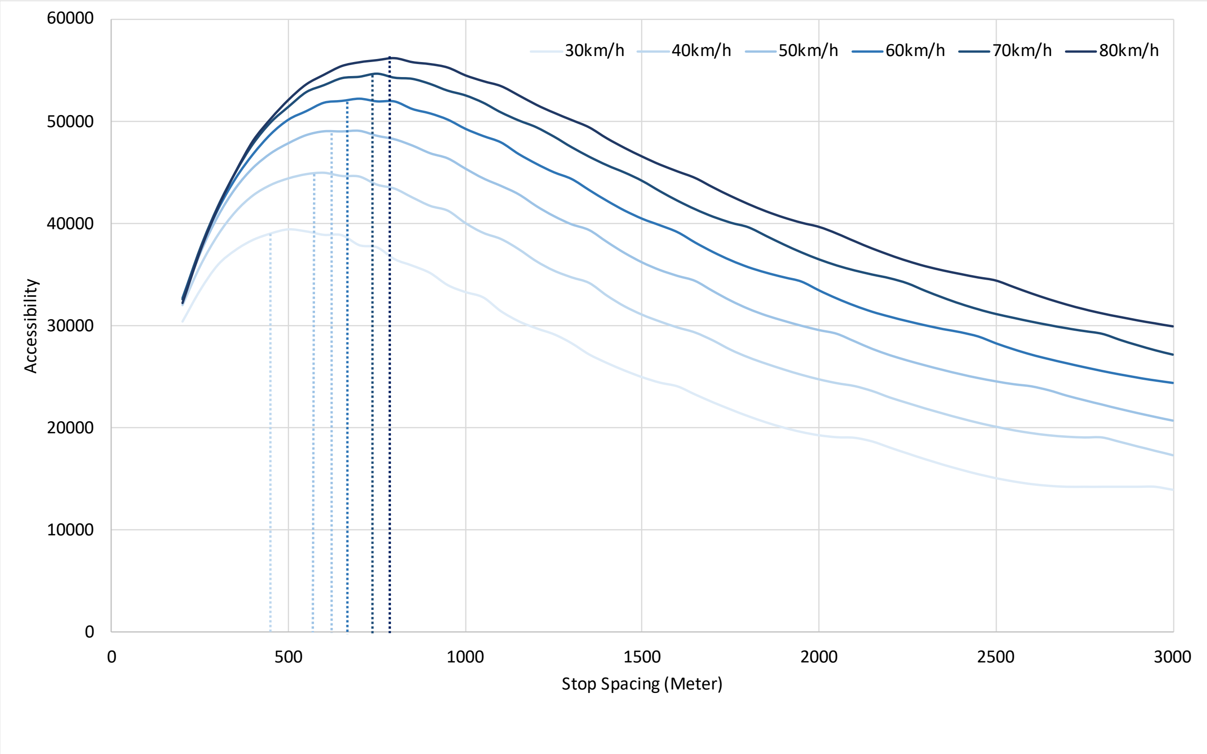

Figure 2. Accessibility and top running speeds.

3.2 Train Acceleration and Deceleration

Train acceleration and deceleration are necessary for reaching top running speed (cruising), and for slowing down before reaching the next station to serve passengers. Greater train acceleration and deceleration improves accessibility by increasing the proportion of on-board time at top-running speed, raising the overall speed. There is limited room for raising the rates of speed change, mostly due to physical acceptance of standing and seated passengers onboard. Standing passengers take up less space, but are more vulnerable to speed changes; most urban rails have standing areas for passengers to increase the capacity of the carriages. Fast acceleration and deceleration raise the risk of passengers losing balance and falling when speed changes exceeds the capacity of the human body to react (Powell and Palacín, 2015). Rate of speed change at around 1.3 $m/s^2$is most often used (National Academies of Sciences, Engineering, and Medicine, 2013, Powell and Palacín, 2015) by urban railway vehicles, and is the default rate for our model. Research on urban rail has shown rates of acceleration close to 2 m/s^2as not acceptable for most of the participants, and a rate of 1 m/s^2 is mostly agreeable (Hiroaki, 1995). This narrow spectrum of physically acceptable rates of speed change defines the range to be studied in this analysis.

Figure 3 shows changes in accessibility by varying the rate of acceleration and deceleration within human acceptable range, using 60 km/h as default running speed. The effect of different rates of speed change on accessibility proves limited, given its narrow range of variation. The improvement in accessibility by raising the acceleration from the current state of practice at 1.3 m/s^2 to the near unacceptable rate at 1.9 m/s^2proves minimal.

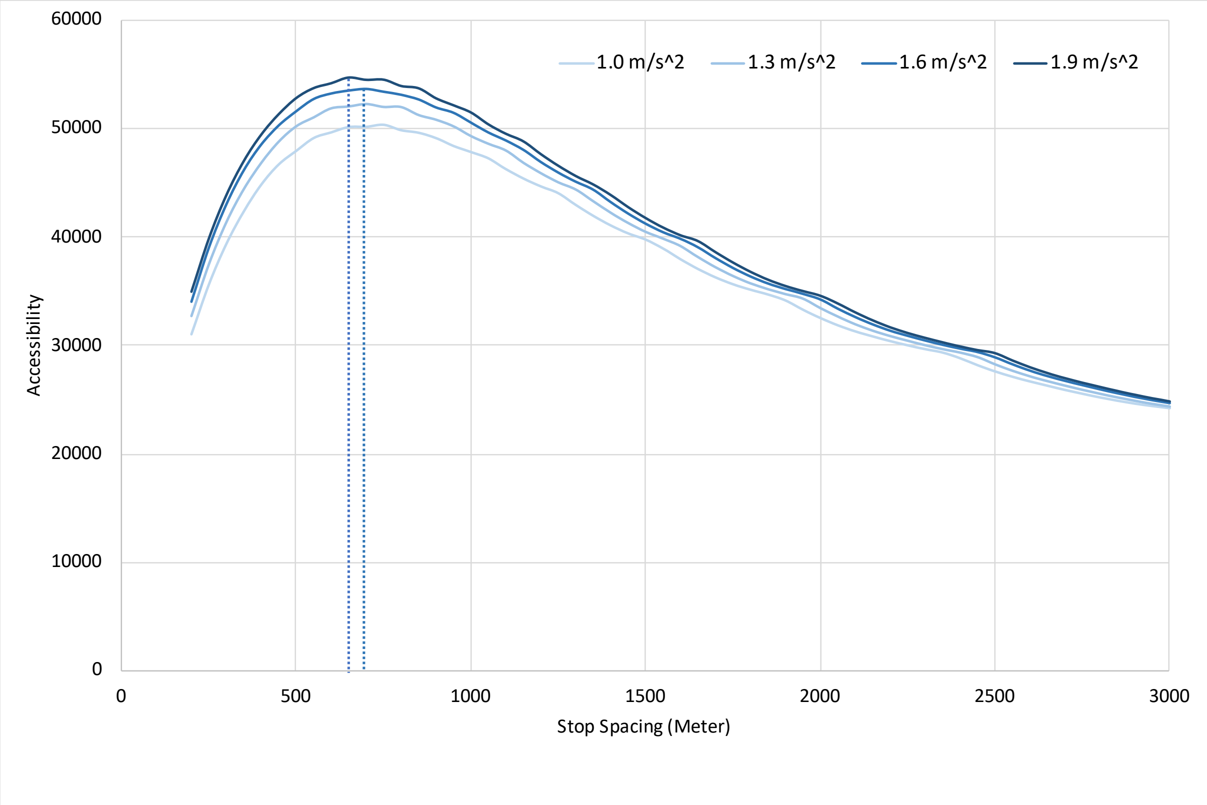

Figure 3. *Accessibility with different rates of speed change*

3.3 Station dwell time

Dwell time is the time a train stopped at station serving passengers. Each additional stop increases interaction between the transit line and the adjacent land, the dwell time that comes with additional stops is a time penalty that affects overall travel speed, line capacity and accessibility. Required dwell time depends on the flow of passengers boarding and alighting the trains, the effectiveness of the flow, and the built-in buffer time. Major components of dwell time include: door open and close time; passenger flow time; time the doors remain open after passenger flow ceases (National Academies of Sciences, Engineering, and Medicine, 2013). There is ample room for improvement with the dwell time by better design of the carriages and by operational improvements; such measures include more train doors and increasing the speed the doors operates, train doors on both sides of carriages, and installation of physical barriers on platform to smooth passenger flow. These measures combined have the potential to significantly reduce station dwell time. Figure 4 plots accessibility change with potential improvement in station dwell time.

Lower dwell time reduces the stop spacing required for optimum accessibility. With closer spaced stops, the reduction in station access distance potentially captures more riders along the transit line, increasing its ridership.

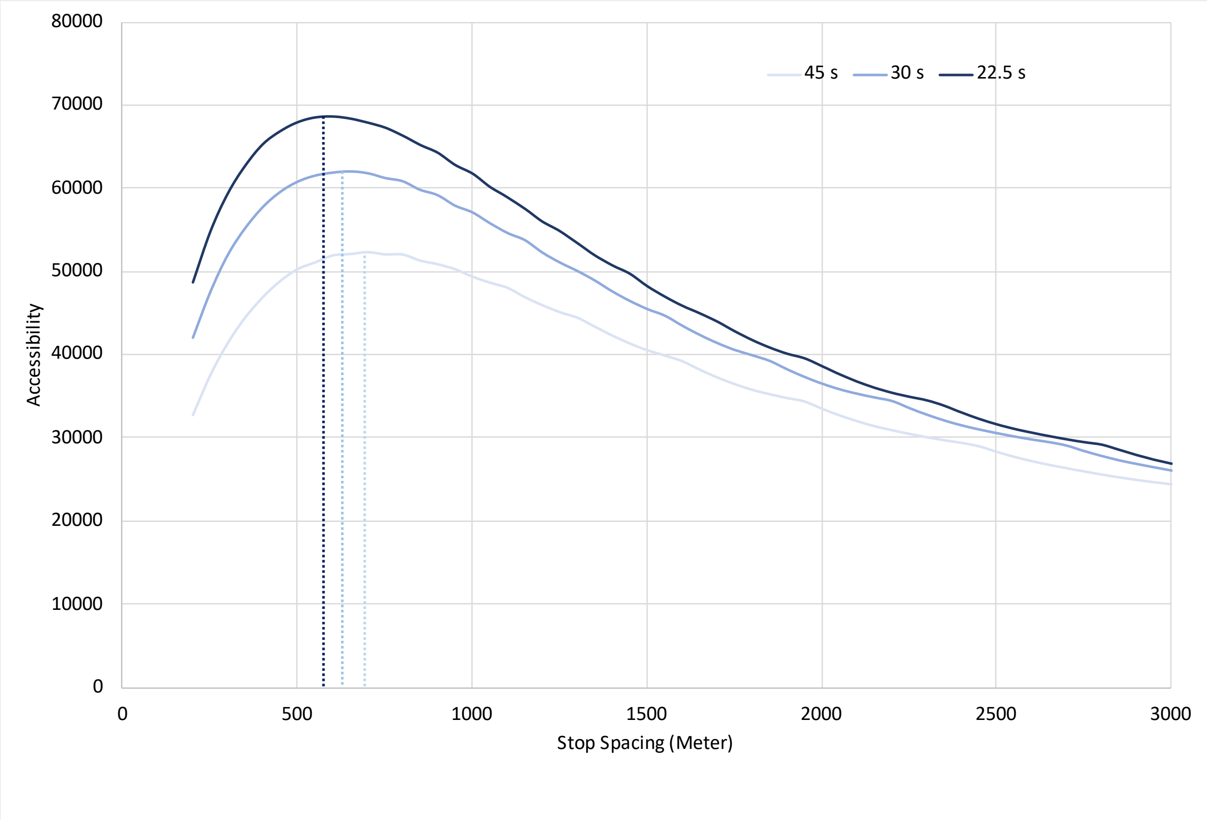

Figure 4. Accessibility under different dwell time

3.4 *Platform configuration*

Stations are not points, the connection time between station entrance and train boarding and alighting depends on station layout, and platform design. While the station layout varies, how passengers board and alight through platforms remains a fundamental problem, and has accessibility implications. A station with ramps on both ends of the platform (e.g. Central Station, Sydney) has the same average walking distance as stations with access to the center, but reduces detour between the train and the actual destination; stations with access on only one end (Redfern, Erskineville Station, Sydney) provide the longest on-platform walking distance (Lahoorpoor and Levinson, 2020). We use Sydney trains as an example to explore how platform design affects accessibility.

Platform design has a noticeable impact on accessibility. For example, a typical Sydney train carriage measures 19.5 meters in length, and a usual 8 car train configuration spans 160 meters (Transport NSW, 2018). The average walking distance on platform depends on the combination of origin and destination station. Passengers traveling through both origin and destination stations that have access to the center of the platform incur an average platform walking distance of 1/2 train length for the whole trip, and 1 train length for stations with ramps on different ends of the train between origin and destination stops. The extra walking distance is longer if their origin and destination is on the end of the platform without an entrance, requiring passengers to backtrack.

Figure 5 shows the accessibility implication of platform design. Tram and street car type urban rails with no measurable on-platform connection time have a modest advantage in accessibility. Though stations with ramps on either end of the platform or a single center ramp have identical on-platform connection time, extra ramps reduce the connection time especially during rush hours when passenger flow exceeds the capacity of exit ramps. In light of the accessibility benefits and the technical practicality, it is recommended that the worst case scenario of having a single ramp on one end of the platform be avoided.

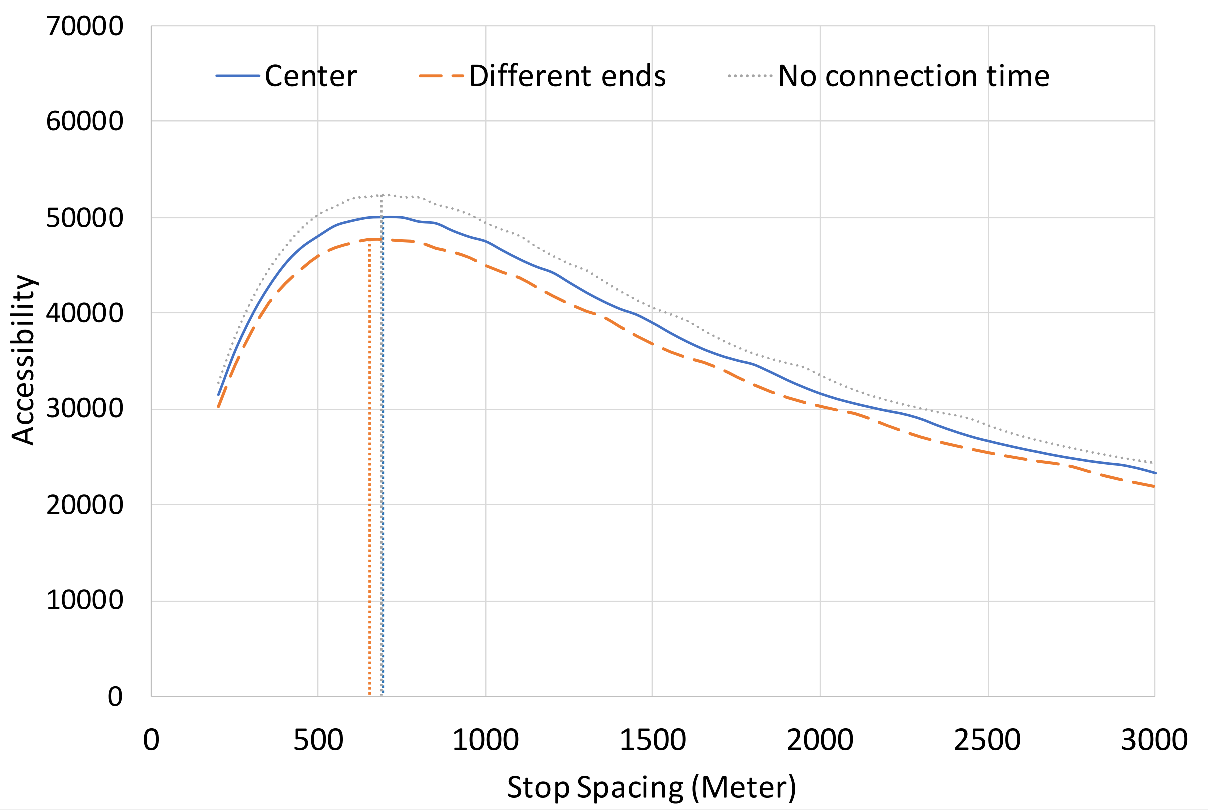

Figure 5. Accessibility with different platform configurations

3.5 Walking speed, bike and ride

The speed passengers access and egress from transit stations affects accessibility. Difference in age, gender and physical stamina cause difference in walking speeds; difficulties in getting to and from transit stations as a result of being physically disadvantaged can potentially cause equity issues. Docked and dock-less bike sharing provides significant speed improvement. In this study, the use of bicycles is treated as having a higher walking speed, and a 16 km/h (10 mph) is used (El-Geneidy et al., 2007).

Effects of varying walking speeds are shown in Figure 6. Slower walking speeds among younger and older travelers, and the physically disabled, may reduce accessibility compared to more physically capable groups. This disadvantage, however, appears small in proportion and should not be a major cause of concern for equity issues. The use of bikes greatly improves accessibility.

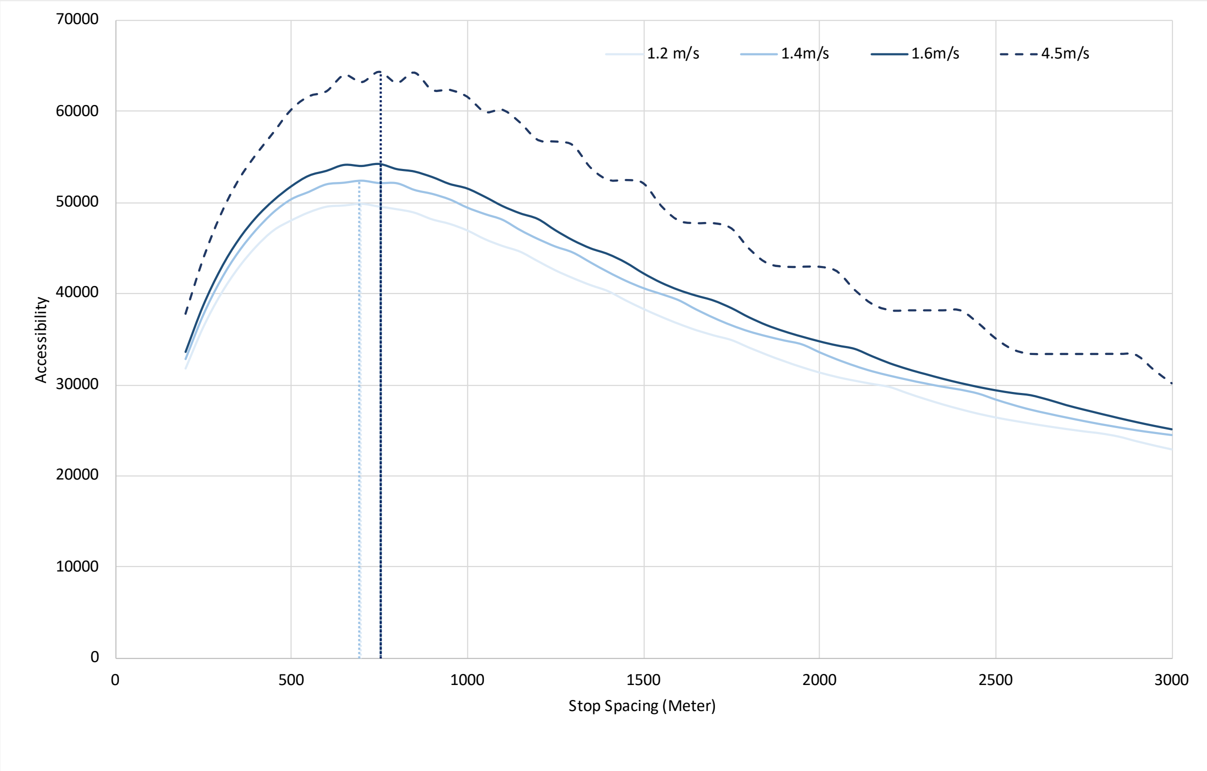

Figure 6. Accessibility and Speed of Station Access/Egress

Integration of bikes and public transport expands accessibility. There are three pronged accessibility benefits of the bike-and-ride mode, including reduced station access and egress time, potentially expanded station service areas and a higher patronage of transit service by people within service areas. As a feeder service to transit, biking not just increases the speed of station access, the distance people willing to bike might be longer than they are willing to walk (Iacono et al., 2008), since biking reduces the physical burden. Bike-and-ride is a common mode of access in some European countries like Denmark and Netherlands where public transport is more developed, and it accounts for over a quarter of all access trips (Cervero et al., 2013); in the San Francisco Bay Area, the percentage of access trips by bikes has reached over ten percent (Cervero et al., 2013).

3.6 How operating speed depends on stop spacing

Operating speed measures how fast a train can travel on its route, including station stops (National Academies of Sciences, Engineering, and Medicine, 2013). Shown in Figure 7 is the relationship between operating speed and stop spacing, based on Equation 7. The initial increase in stop spacing notably raises operating speed, but there are diminishing returns to operating speed; further extending stop spacing results in proportionally less speed improvement. The operating speed approaches the top running speed (60 km/h) with infinitely long stop spacing; with stop spacing optimized for accessibility, actual operating speed reaches less than half of the top speed.

Unlike accessibility which has a convex curve and peaks with a certain stop spacing, the operating speed increases monotonically at a slower rate with longer stop spacing. This implies that for two stop spacing configurations that produce the same level of accessibility, the stop spacing with a lower operating speed (shorter stop spacing) focuses more on the local accessibility, where jobs reachable are clustered within a short linear distance along the transit route; hence it is a more suitable choice for reinforcing downtown or CBD. The same level of accessibility reached with a higher operating speed has a wider spatial distribution of job opportunities, which would be ideal for extending the envelope of CBD. Selection of the stop spacing dictates not just the level of accessibility, but also the spatial distribution of accessible opportunities, so it requires a conscious decision on the objective of the transit system, and its intended area and population.

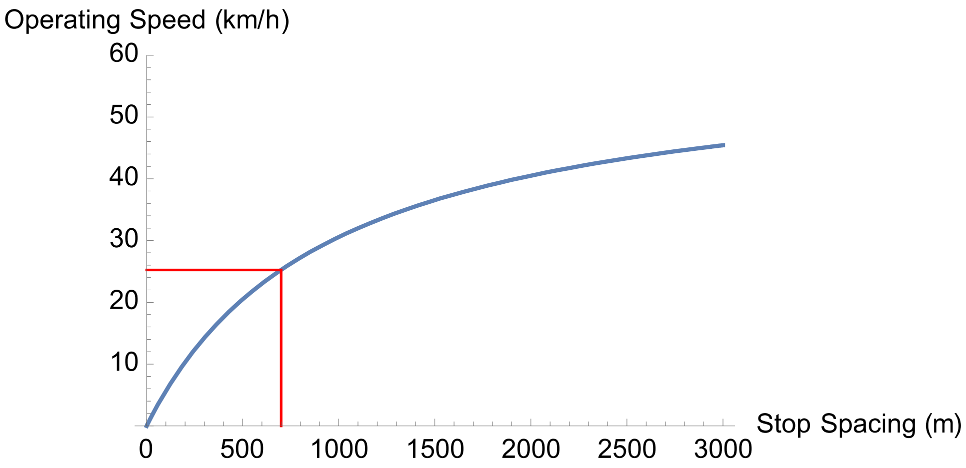

Figure 7. How Operating Speed Depends on Stop Spacing

4. Conclusions

This study finds there exists a stop spacing that maximizes person-weighted accessibility for fixed route transit services. For a transit route, the optimal stop spacing depends on the characteristics of the transit vehicle, mostly its speed in operation, and gate configurations. We show that in transit planning, optimizing for accessibility is not a situation where building more stops (thus increasing infrastructure and operational costs) will automatically improves accessibility; on the contrary, building more stops beyond the optimal number will lower accessibility. Basically, we show that there is an optimum balance between adding more access point through more stations, with how much transit service is slowed down by these additional stops. We suggest that the accessibility goal be considered during the transit planning stage.

For transit systems that have already past the planning and construction phases, some transit operational changes improve accessibility more effectively than others. We list the general guidelines for operationally improving transit accessibility.

- Reduce station dwell time by managing passenger flows, facilitating boarding and alighting;
- Maintain a moderate cruising speed for transit vehicles through managing transit right-of-way;
- Implement stop-skipping;
- Integrate bike-and-ride for transit.

Reducing station dwell time through managing passenger flows, or introducing entrances and exists that open on both ends of the station platform has the most significant improvement on accessibility, and may be the most technically feasible measure. Lower dwell time also allows for closer stop spacing, which benefits ridership. Raising and maintaining a moderate cruising speed for trains (e.g. 60-70 km/h) produces satisfactory levels of accessibility, further increase in speed has diminishing returns to accessibility improvement. Higher rates of acceleration and deceleration only marginally improves accessibility while discomforting passengers, thus is not recommended for implementation.

Well-studied and accepted design objectives often emphasize minimizing total costs. It has been noted that bus services (low speed, close stop spacing) often have the lowest total cost, but the more expensive and faster light-rail can outperform bus through its speed advantage (Tirachini et al., 2010); this is consistent with the optimal stop spacing, in that faster services generally have better accessibility, and fewer stops. More expensive transit options that provide better accessibility might be worth the additional investment; for instance, when one option provides much better accessibility, but is only marginally more expensive, especially when it increases patronage and fare box recovery.

Different types of transit have different requirements for stop spacing in order to maximize access. Faster services with exclusive right-of-way generally need longer stop spacing than slower moving tram-type services in mixed traffic. Transit services with low cruising speeds are inherently disadvantaged in providing accessibility, and has limited room for operational improvements; although they may have lower access costs as they avoid some travel time associated with larger, grade-separated train stations. Integration of bike and transit should be encouraged, for it provides substantial improvement in accessibility. Substitution of biking for walking allows the optimum accessibility to be achieved under longer stop spacing, which allows for higher operating speed of transit vehicles. Hence transit stations need to be spaced strategically with accessibility as an important consideration.

Stop spacing has significant implications for accessibility, and the effect would be long lasting due to the near-permanent nature of the transport infrastructure. While operating cost, and other considerations may change over time with higher levels of automation, the accessibility impact of stop locations are more fundamental, and longer lasting. This study contributes by raising the importance and accessibility implications of stop spacing, and demonstrates that the observed pattern of longer spacing for faster services is generally consistent with accessibility maximization.

References

Alonso, B., Moura, J. L., dell'Olio, L., and Ibeas, Á. (2011). Bus stop location under different levels of network congestion and elastic demand. *Transport*, 26(2):141–148.

Boisjoly, G. and El-Geneidy, A. M. (2017). The insider: A planners' perspective on accessibility. *Journal of Transport Geography*, 64:33–43.

Ceder, A. A., Butcher, M., and Wang, L. (2015). Optimization of bus stop placement for routes on uneven topography. *Transportation Research Part B: Methodological*, 74:40–61.

Cervero, R., Caldwell, B., and Cuellar, J. (2013). Bike-and-ride: build it and they will come. *Journal of Public Transportation*, 16(4):5.

Cervero, R., Murakami, J., and Miller, M. (2010). Direct ridership model of bus rapid transit in Los Angeles county, California. *Transportation Research Record*, (2145):1–7.

Daganzo, C. F. (2010). Structure of competitive transit networks. *Transportation Research Part B: Methodological*, 44(4):434–446.

Debrezion, G., Pels, E., and Rietveld, P. (2007). The impact of railway stations on residential and commercial property value: a meta-analysis. *The Journal of Real Estate Finance and Economics*, 35(2):161–180.

dell'Olio, L., Moura, J., and Ibeas, A. (2006). Bi-level mathematical programming model for locating bus stops and optimizing frequencies. *Transportation Research Record* (1971):23–31.

El-Geneidy, A. M., Krizek, K. J., and Iacono, M. (2007). Predicting bicycle travel speeds along different facilities using GPS data: A proof of concept model. In *Proceedings of the 86th annual meeting of the Transportation Research Board, compendium of papers*. TRB Washington, DC, USA.

El-Geneidy, A. M. and Levinson, D. M. (2006). Access to destinations: Development of accessibility measures.

Ermagun, A., Levinson, D., et al. (2015). Accessibility and transit performance.

Fernandez, R. M. (1994). Race, space, and job accessibility: Evidence from a plant relocation. *Economic Geography*, 70(4):390–416.

Giuliano, G., Gordon, P., Pan, Q., and Park, J. (2010). Accessibility and residential land values: some tests with new measures. *Urban Studies*, 47(14):3103–3130.

Guerra, E., Cervero, R., and Tischler, D. (2012). Half-mile circle: Does it best represent transit station catchments? *Transportation Research Record* (2276):101–109.

Hansen, W. G. (1959). How accessibility shapes land use. *Journal of the American Institute of Planners*, 25(2):73–76.

Hiroaki, S. (1995). Ability to withstand sudden braking. *Railway Res Rev*, 52(5):18–21.

Iacono, M., Krizek, K., and El-Geneidy, A. M. (2008). Access to destinations: How close is close enough? estimating accurate distance decay functions for multiple modes and different purposes.

Ibeas, Á., dell'Olio, L., Alonso, B., and Sainz, O. (2010). Optimizing bus stop spacing in urban areas. *Transportation Research part E: Logistics and Transportation Review*,46(3):446–458.

Ingram, D. R. (1971). The concept of accessibility: A search for an operational form. *Regional Studies*, 5(2):101–107.

Kikuchi, S. and Vuchic, V. R. (1982). Transit vehicle stopping regimes and spacings. *Transportation Science*, 16(3):311–331.

Lahoorpoor, B. and Levinson, D. M. (2020). Catchment if you can: The effect of station entrance and exit locations on accessibility. *Journal of Transport Geography*, 82:102556.

Levinson, D. M., Giacomin, D., and Badsey-Ellis, A. (2016). Accessibility and the choice of network investments in the London Underground. *Journal of Transport and Land Use*,9(1):131–150.

Marchetti, C. (1994). Anthropological invariants in travel behavior. *Technological Forecasting and Social Change*, 47(1):75–88.

Mayor, K., Lyons, S., Duffy, D., and Tol, R. S. (2012). A hedonic analysis of the value of rail transport in the greater Dublin area. *Journal of Transport Economics and Policy (JTEP),*46(2):239–261.

McNeil, N., Dill, J., DeVitis, D., Doubleday, R., Duncan, A., and Weigand, L. (2017). Manual on pedestrian and bicycle connections to transit. Technical report.

National Academies of Sciences, Engineering, and Medicine (2013). Transit capacity andquality of service manual,third edition. *Washington, DC: The National Academies Press*.

Owen, A. and Levinson, D. M. (2015). Modeling the commute mode share of transit using continuous accessibility to jobs. *Transportation Research Part A: Policy and Practice*,74:110–122.

Powell, J. and Palacín, R. (2015). Passenger stability within moving railway vehicles: limits on maximum longitudinal acceleration. *Urban Rail Transit*, 1(2):95–103.

Saka, A. A. (2001). Model for determining optimum bus-stop spacing in urban areas. *Journal of Transportation Engineering*, 127(3):195–199.

Tirachini, A., Hensher, D. A., and Jara-Díaz, S. R. (2010). Comparing operator and users costs of light rail, heavy rail and bus rapid transit over a radial public transport network. *Research in Transportation Economics*, 29(1):231–242.

Transport NSW (2018). Technical drawings and specifications. Transport NSW.

Van Nes, A. and Stolk, E. (2012). Degrees of sustainable location of railway stations: Integrating space syntax and node place value model on railway stations in the province of north holland's strategic plan for 2010-2040. In *Proceedings of the 8th International Space Syntax Symposium, January 3-6, 2012, Santiago de Chile, Chile*.

Van Nes, R. and Bovy, P. H. (2000). Importance of objectives in urban transit-network design. *Transportation Research Record*, 1735(1):25–34.

Wachs, M. and Kumagai, T. G. (1973). Physical accessibility as a social indicator. *Socio-Economic Planning Sciences*, 7(5):437–456.

Walker, J. (2012). *Human transit*. Island Press

Wickstrom, G. V. (1971). Defining balanced transportation-a question of opportunity. *Traffic Quarterly*, 25(3).

Wirasinghe, S. C. and Ghoneim, N. S. (1981). Spacing of bus-stops for many to many travel demand. *Transportation Science*, 15(3):210–221.

Wu, H., Levinson, D., and Owen, A. (2019a). Commute mode share and access to jobs acrossus metropolitan areas. *Environment and Planning B: Urban Analytics and City Science,* page 2399808319887394.

Wu, H., Levinson, D., and Sarkar, S. (2019b). How transit scaling shapes cities. *Nature Sustainability*, 2(12):1142–1148.

Appendix A - Derivation of station access time

The station access time used in measuring accessibility is the person weighted average travel time for transit riders whose residence is within the transit service area (defined as 800 meters Manhattan distance) to the closest train station. The model assumes a linear decay function with 100% trip likelihood at zero distance to station, and 0% at 800 meters at the edge of the service area.

Population served by each of the transit station (Pc) is calculated as the original residential density (ρ) adjusted by a linear distance decay to reflect trip likelihood, as shown in Equation 8. Overlapping service areas reduces population covered by each of the station. A residential density of 5600 persons/km2 is assumed, although the relation between the density of transit riders and distance is scalable, so the assumption on density does not affect the person-weighted station access time.

$$P_c = \begin{cases} 4\int_0^{\frac{\sqrt{2}}{2}L}[(\rho - k\sqrt{2}x)2x]\,dx & if\ D_s \geq 2L \\ 4\int_0^{\frac{\sqrt{2}}{2}L}[(\rho - k\sqrt{2}x)2x]\,dx \ - \ 4\int_0^{\frac{\sqrt{2}}{2}(L-\frac{D_s}{2})}[(\rho - k\frac{D_s}{2} - k\sqrt{2}x)2x]\,dx & if\ D_s < 2L \end{cases} \tag{8}$$

P_c: population covered by each of the transit station

Cumulative walking distance to transit station for all riders within a service area (D_c) isgiven by Equation 9.

$$d_{c=}\begin{cases} 4\int_0^{\frac{\sqrt{2}}{2}L}[(\rho - k\sqrt{2}x)2x]\sqrt{2}\,xdx & if\ D_s \geq 2L \\ 4\int_0^{\frac{\sqrt{2}}{2}L}[(\rho - k\sqrt{2}x)2x]\sqrt{2}\,xdx - 4\int_0^{\frac{\sqrt{2}}{2}\left(L-\frac{D_S}{2}\right)}\left[\left(\rho - k\frac{D_s}{2} - k\sqrt{2}x\right)2x\right]\left(\sqrt{2}x + \frac{D_s}{2}\right)dx & if\ D_s < 2L \end{cases} \tag{9}$$

The station access time for coverage area of a transit station is derived through dividing the total walking distance (derived in Equation 8) by the total service population from the service area of the origin transit stop (obtained in Equation 9), and the average walk or bike speed $\boldsymbol{v_w}$. The resulting population weighted average station access time is Equation 10.

$$T_a = \begin{cases} \frac{L}{2v_w} & if\ D_s \geq 2L \\ \frac{D_S^3 - 4LD_S^2 + 16L^3}{(4D_S^2 - 24LD_s + 48L^2)v_w} & if\ D_s < 2L \end{cases} \tag{10}$$

Appendix B - Derivation of operating speed

The number of stops a train makes on a one-way trip is intrinsically a discrete number. Here we derive the number of stops as a continuous variable of the total route distance divided by stop spacing between every two stops, i.e. $N_s = \frac{D}{D_s}$. The distance traveled on the rail track (D) during a one-way trip comprises the distance run at top speed, and distance used for speed changes. This rail travel distance is given by Equation 11.

$$D = \left(\frac{v^2}{2a} + \frac{v^2}{2a}\right) \cdot \frac{D}{D_s} + v \cdot T_{top} \tag{11}$$

The amount of time the train runs at top (cruising) speed is given by Equation 12.

$$t_{o2} = \frac{D}{v}(1 - \frac{1}{D_s}(\frac{v^2}{2a} + \frac{v^2}{2a})) \tag{12}$$

The total on-board travel time consists of the time spent for acceleration, deceleration, stopped (dwell time), and the time running at top speed, shown in Equation 13.

$$T_o = \frac{D}{D_s}\left(\frac{v}{a} + \frac{v}{d} + t_{o4}\right) + \frac{D}{v}(1 - \frac{1}{D_s}(\frac{v^2}{2a} + \frac{v^2}{2a})) \tag{13}$$

The operating speed (including station stops) as a function of stop spacing Ds is obtained by dividing rail travel distance (Equation 11) by on-board travel time (Equation 13), shown in Equation 14 below.

$$v_o = \frac{D}{T_o} = \frac{v \cdot D_s}{v^2\left(\frac{1}{2a} + \frac{1}{2b}\right) + v \cdot t_{o4} + D_s} \tag{14}$$