

1 Evaluating the value of new metro lines using route diversity measures:
2 the case of Hong Kong's Mass Transit Railway system
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Abstract

The Hong Kong Mass Transit Railway (MTR) is one of the most profitable and efficient urban rail transit systems in the world. It serves as the backbone of the Hong Kong public transportation network, and is still under expansion to increase its coverage and service quality. Nevertheless, frequent disruptions have caused the public to doubt the network's resilience, prompting a number of studies of how new infrastructure investment could promote a more resilient transportation system. It is widely understood from topological theory that new lines do not necessarily bring equal benefits to all parts of such a network. To examine the distribution of the effects of new lines, we adopted a relatively new network performance measure of route diversity, defined as the number of behaviorally effective routes between each origin-destination (O-D) pair in the network. Based on disaggregated information acquired explicitly from the travelers' perspective, this paper presents a longitudinal analysis to evaluate the benefit of new lines from two specific perspectives: (a) the distribution of the effects of different expansion plans, revealing that certain groups or areas are more likely to benefit from the expansion; and (b) the effects of different expansion plans on network vulnerability, which facilitates the identification of vulnerable components and prioritization of alternative metro projects with complementary effects. The proposed analytical method is applied to investigate the MTR expansion plan from 2019 to 2031. The insights from this study will be helpful for increasing the value of planning suggestions to foster a more resilient transportation system.

Keywords: Public transport, Network expansion, Resilience, Route diversity, metro

1. Introduction

Resilience is a critical element of a sustainable system and has become an increasing focus of research (Faturechi and Miller-Hooks, 2014; Gu et al., 2020; Wan et al., 2018). Resilience can be defined in reference to “the 4Rs,” namely robustness, redundancy, resourcefulness, and rapidity, from which a system derives two primary abilities: resisting and recovering from the effects of perturbation (Bruneau et al., 2003). The existence and importance of resilience have been demonstrated by research into transportation systems faced with both natural disasters (such as earthquakes (Bono and Gutiérrez, 2011) and flooding (Lu et al., 2014)) and social events, either externally generated (such as terrorist attacks (Lordan et al., 2014) and social disputes (Loo and Leung, 2017)) or planned (such as major sporting events (Parkes et al., 2016)). Both natural and human-induced adverse events raise the need for government agencies and the community to broaden the availability of alternative routes to strengthen the resilience of transportation networks to adverse events.

Resilience can be improved in several aspects, such as reducing the failure probabilities, consequences of failures, and time to recovery (Bruneau et al., 2003). Using those measures, this study examines how building new lines enables a public transportation network to better withstand disruptive events and their consequences. Indeed, building new transit lines is a crucial consideration in the growing field of transportation resilience. Jenelius and Cats (2015) evaluated the robustness of a new cross-radial line in Stockholm in terms of travel time under disruptions of supply and demand. Cats (2016) studied the network development plan in Stockholm, Sweden, and concluded that it would improve the network robustness by reducing the average travel time losses during disruptions. Hong et al. (2017) investigated the effects of different expansion plans on the vulnerability of subway network in Wuhan, China, and identified the optimal plan from the network redundancy perspective. Zhu et al. (2018) investigated the appraisal of alternative lines and their effects on the network performance during adverse events using the case of line extension of a network in Beijing, China. Nian et al. (2019) evaluated the benefit of different alignments of new lines with respect to reducing network vulnerability in Shanghai, China. Chen et al. (2014) investigated the metro network in Guangzhou, China, and found that the gains from network development in terms of connectivity and accessibility were not spread evenly among regions, emphasizing the importance of matching developments with different regional situations. Weckström et al. (2019) investigated the metro extension in Helsinki, Finland, and argued that the unequal distribution of benefits and burdens in terms of travel time and transfers had been overlooked in an aggregate manner. Unlike the others, the latter two studies provided evidence for the necessity of studying the distribution of network extension effects in detail. This requires a disaggregated assessment approach. However, their findings may not be universally applicable due to the specific features of their case studies and research contexts. This highlights that more empirical evidence is needed to assess the distribution of the effects of new lines on resilience.

In this context, this study aimed to evaluate the benefit of new lines in public transit with a case study in Hong Kong. Supplementing traditional measures of increased utility due to shorter travel times, we adopted a relatively new index – route diversity – to evaluate network performance explicitly from the travelers’ perspective (Xu et al., 2018a). Within this analytical framework of route diversity, we can examine the redundancy value of new lines and trace the changes both in general and for specific origin-destination (O-D) pairs resulting from major expansions or additions to the transit network. The effects on network robustness are evaluated by vulnerability assessment in terms of the number of behaviorally effective paths during disruptions. With the disaggregated information provided by the proposed measure of route

diversity, the temporal evolution of the network's properties and its benefits to specific groups can be effectively examined.

2. Literature Review

There is no single definition of transportation resilience, but it is commonly understood to relate to system performance under perturbations (Gu et al., 2020). Bruneau et al. (2003) introduced four concepts of resilience applicable to transportation studies, namely robustness, redundancy, resourcefulness, and rapidity, and this interpretation has been widely adopted in the context of transportation. Robustness and redundancy evaluate the network's resistance to perturbation, while rapidity and resourcefulness are related to the ability to recover. A recent trend in transportation planning is to argue that new lines add value in terms of robustness and redundancy and thus contribute to a more resilient transportation system. The building of railways represents a significant change to the local area and affects a considerable population. The potentially huge effects of new metro lines have attracted interest from researchers in a variety of fields, studying issues such as travel behaviors (Loo, 2009; Weckström et al., 2019) and land use (Mejia-Dorantes et al., 2012; Tan et al., 2019). In the context of network performance, both traditional utility assessment during normal operations (Chen et al., 2014; Kim and Song, 2015; Song et al., 2018; Weckström et al., 2019) and vulnerability assessment during disruption scenarios (Cats, 2016; Hong et al., 2017; Jenelius and Cats, 2015; Nian et al., 2019; Zhu et al., 2018) have been studied. Within the broad concept of transportation resilience, vulnerability analysis is often the first step to assess the ability of a network to resist the effects of perturbations. Indeed, vulnerability is a component enshrined in the concept of resilience.

It has been found that network topology influences network resilience in terms of resistance and recovery abilities (Zhang et al., 2015). Many studies have investigated the topological characteristics of metro networks with graphs and complex network indices to evaluate the network performance. The metrics used in such research can be divided into connectivity and accessibility measures of the network topology. Wang et al. (2014) studied the evolution of the air transportation network in China and identified an improvement in connectivity based on the rising alpha, beta, and gamma indices. Chen et al. (2014) also adopted the alpha, beta, and gamma indices to quantify the overall metro network growth in Guangzhou, China. However, being solely based on the number of nodes and links, those three indices have a limited capacity to reveal structural differences between networks of equal size. López et al. (2017) conducted accessibility-based network vulnerability analysis by investigating the changes in node closeness and betweenness in different disrupted scenarios. Sarlas et al. (2020) proposed a new centrality measure called betweenness-accessibility to measure the accessibility of stations during disruptions, regarding both the general population and the particular case of work commuters. Various graph-based analyses have been applied, but all share the objective of quantitatively studying the spatial distribution of travel opportunities based on shortest paths, neglecting the route choice behaviors of travelers.

The issues of transportation resilience concern not only transit networks or particular projects themselves as physical entities to support the prevailing demands, but also the travelers' responses to the provision of optional routes between origins and destinations during disruptive events. Limitations of the existing performance measures have spurred the development of new metrics by introducing transportation engineering characteristics into a network-based methodology. Hawas et al. (2016) presented an approach for accessibility based on route diversity to measure network effectiveness. Route diversity represents the number of routes accessing to and from different regions via transit services. However, the calculation of all

possible routes for any O-D pair, although it may be feasible and justified in a relatively simple network in Abu Dhabi, United Arab Emirates, may not be applicable in more extensive and complex networks. Xu et al. (2018a) presented route diversity measures based on the concept of reasonable routes, taking the view that travelers would be unlikely to consider all possible routes as realistic alternatives. Thus, only routes that are reasonably quick relative to the shortest path are considered when assessing the network accessibility performance. This is especially useful for vulnerability analysis by accounting for the fact that commuters are more likely to consider shorter detoured routes, given an acceptable travel cost, as reasonable alternatives when the primary or secondary route is not available. Yang et al. (2017) demonstrated the feasibility of route diversity metrics for the Beijing metro network and identified the vulnerable stations. Jing et al. (2019) showed how such metrics could better uncover the existence of alternative paths compared with the standard measures of network connectivity for four different metro networks. The proposed topological measure evaluated for each O-D pair can also provide disaggregated information explicitly from the travelers' perspective. The redundancy measures not only provide information on alternative routes to travelers to minimize the impact of disruptions but also aid recovery and redesign strategies by making transportation networks more resilient against disruptions. Theoretical developments in topological analysis have revealed many useful insights in people-oriented planning.

The route diversity measure fulfills various purposes: (1) reflecting the reality that passengers may not reroute immediately and optimally when networks change due to new lines or disruptions; and (2) providing disaggregated information at the O-D level to reveal the disparate topological effects of different new lines. Following the direction of Xu et al. (2018), we customize the route diversity measures to our longitudinal analysis of the evolutions of networks. The details of the algorithmic procedure can be found in Section 4.

3. Case study

As one of the most efficient public transportation systems in the world, our case study in Hong Kong is well known for its successful transit-oriented development and self-financing public transportation. Approximately 90% of the 12.9 million daily motorized trips in Hong Kong are made by public transportation (Transport Department, 2019), one of the highest rates of any developed region worldwide. With the government's stated policy of "using railways as the backbone of Hong Kong's public transportation system," the Hong Kong metro network (Mass Transit Railway, MTR) accounts for 43.4% of the average daily public transportation trips (Transport Department, 2019). Fig. 1 shows the general spatial structure of the city, which comprises Hong Kong Island, Kowloon, and the New Territories. The main urban areas of the city lie on either side of Victoria Harbour. As of 2019, the MTR has 10 operational lines and 93 stations with a total length of 187.4 km. The MTR is experiencing rapid expansion to meet the increased travel demand in recent years. Herein, the five major line expansions recommended by the Railway Development Strategy (Transport and Housing Bureau, 2014) are used as the case study (Fig. 1). Several new lines are planned to be in operation by 2031, bringing the total railway length to 235.3 km, as shown in Table 1. The rail share of overall daily motorized trips will increase to about 50% with the completion of several railway projects. However, metro networks are vulnerable to incidents that threaten the efficiency of the overall system. Recently, such failure events have occurred more frequently in Hong Kong (RTHK News, 2019a, 2019b), and the regularity of serious disruptions has prompted the public to wonder whether the new lines will add redundancy (i.e., alternative routes) to the existing MTR system.

Table 1

The spatial extension of the MTR network in Hong Kong (Transport and Housing Bureau, 2014).

Year	Lines	Stations ⁽¹⁾	Links	Route length (km)	T_N (mins)	D_N	P[1]	New railway lines
2019	10	93	99	187.4	29.47	1.116	0.587	-
2021	10	98	114	204.4	27.01 (-8.35%)	1.137 (+1.88%)	0.567	Shatin to Central Link ⁽²⁾
2023	11	101 ⁽³⁾	118	215.1	27.93 (+3.41%)	1.145 (+0.70%)	0.566	Northern Link
2025	12	105	123	222.9	27.63 (-0.01%)	1.147 (+0.17%)	0.547	East Kowloon Line
2026	13	110	129	230.3	27.93 (+0.01%)	1.151 (+0.35%)	0.533	South Island Line (West)
2031	14	112	133	235.3	26.67 (-0.05%)	1.165 (+1.22%)	0.555	North Island Line

Note: (1) Not including the Light Rail and the Airport Express; (2) comprising two parts of the extended segments of the existing East Rail Line and Ma On Shan Line; (3) including new stations at Hung Shui Kiu and Tung Chung West.

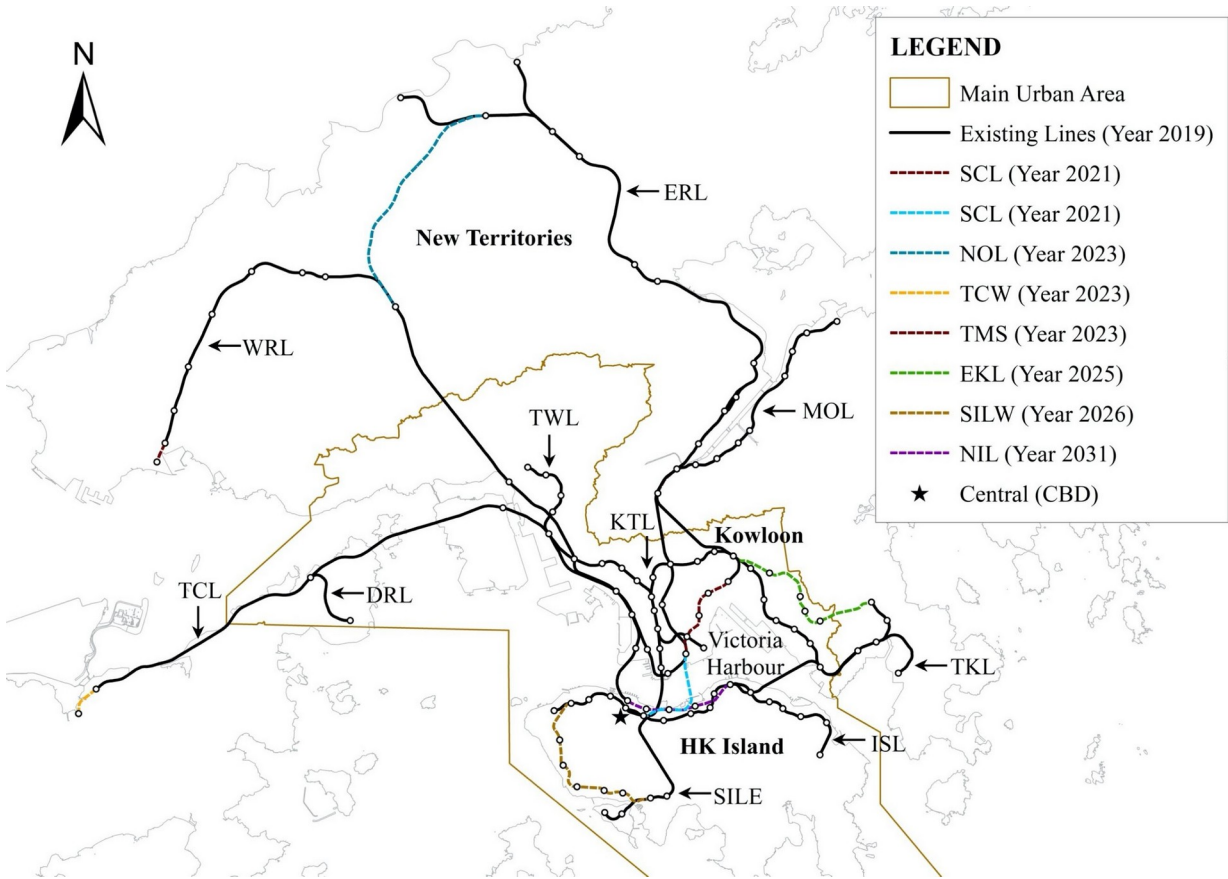


Fig. 1. Map of the Hong Kong MTR system in 2031

To better illustrate the ring-radial network structure, following the study of Roberts et al. (2016), we transform the MTR map into a concentric circle map as shown in Fig. 2. In a radial-centric network, each radial segment connects two outer-city areas as it passes through the city center. However, such a network can also contain circumferential segments, which intersect the radial lines to allow transfer between them, thus constituting a route-diverse network. This network structure generates bottlenecks along the circumferential line segments where branches merge and lines intersect. As we can see, most of the new lines will be in the circumferential

form. The Northern Link (NOL), East Kowloon Line (EKL), South Island Line West (SILW), and North Island Line (NIL) can be considered as forming a partial ring that integrates the network by allowing shortcuts, thus enhancing robustness. The only exceptions are the new line segments named the Shatin to Central Link (SCL). These consist of two parts: a southern extension of the Ma On Shan Line (MOL) connecting with the West Rail Line (WRL) to form the new Tuen Ma Line (TML), and a southern extension of the East Rail Line (ERL) to the Island Line (ISL) to form the new North-South Line (NSL). The SCL will improve the connections between the northern and western inner suburbs and provide a more direct cross-harbor alternative for the northern area.

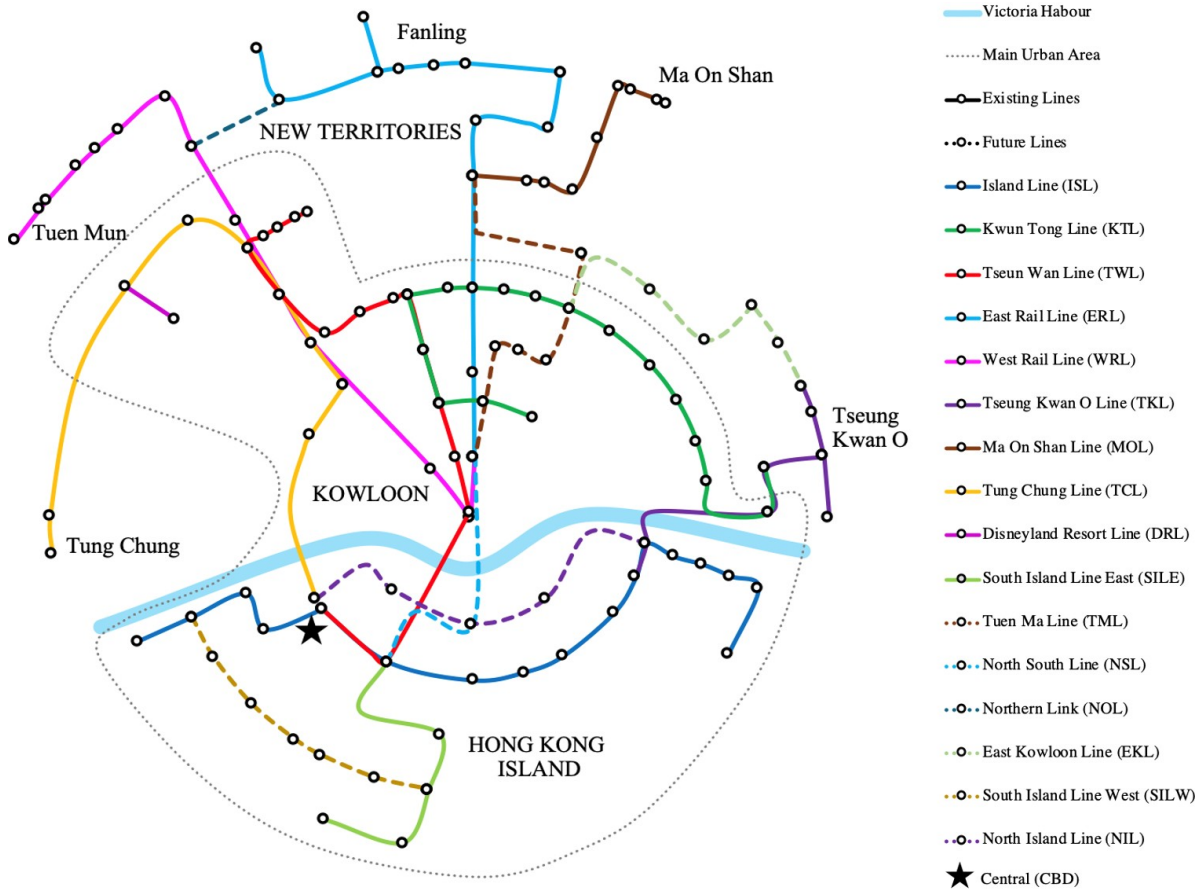


Fig. 2. The concentric circle representation of the Hong Kong MTR system in 2031

4. Methodology

A method to analyze the value of new metro lines with respect to the topology of the network is proposed. This method entails performance evaluation of route diversity and travel time under normal operating conditions, and vulnerability analysis by a full consideration of possible station failure scenarios. The following sub-sections describe the network representation and the set of routes, followed by the measures of performance and station vulnerability deployed in this study.

4.1 Network representation and basic topological properties

The MTR network is virtualized in a weighted matrix $M(N, A)$, where N is a finite set of nodes (stations) and A is a finite set of links (connections between adjacent stations). Any node in N can be an origin or a destination of an O-D trip. Each link in A is weighted with the time cost attribute c_a . This representation is based on the L-space graph commonly used in studies of public transportation networks from the complex network perspective (Luo et al., 2019). Similar to the representation used by Sun et al. (2015) and Jing et al. (2019), each interchange station in the network matrix is divided into virtual nodes, each of which has a particular node degree. These virtual nodes are considered to be located on separate MTR lines, and the virtual links between those lines determine the required transfer time. This graph representation has two key features.

- (1). It enables simulation by allowing one to add both in-vehicle and transfer time attributes when evaluating the set of reasonable routes, under the assumption that travelers choose their routes based on the time cost.
- (2). It enables comparison by allowing simple modification of graphs when existing stations become new interchange stations through the addition of virtual stations and links as new connections.

4.2 Assessment of route diversity

We are interested in the route set of each O-D pair in both regular operation and disruptive events. Considering that travelers do not necessarily choose the shortest path, the route choice factors, which are related to the travelers' level of knowledge about the alternative routes, are implicitly considered. This accommodates the likelihood that some travelers will choose their routes with imprecise knowledge of the disrupted network during an actual event, and there may well be some heterogeneity in the routes chosen.

A reasonable route between O-D pair (m, n) is defined as a route whose links are reasonably short relative to the shortest path (Leurent, 1997; Xu et al., 2018a). The link constraint can be described mathematically as:

$$(1 + \tau_m^a)(c_m(a_h) - c_m(a_t)) \geq c_a, \forall a \in A_k, m \in N \quad (1)$$

where a_h and a_t are the head and tail nodes of link a ; $c_m(a_h)$ and $c_m(a_t)$ are the minimum time cost from origin m to the head and tail of link a , respectively; τ_m^a is an acceptable elongation ratio for link a with respect to origin m , and τ is usually set to 1.5 for urban areas (Tagliacozzo and Pirzio, 1973); and A_k is the set of links in route k .

Sets of reasonable routes for each O-D pair (m, n) $K_{mn} = \{R_1, R_2, \dots, R_i\}$ are obtained using Eq. (1). With the travel time of each reasonable route t_i , the average travel time T_{mn} is calculated as:

$$T_{mn} = \frac{1}{R_{mn}} \sum t_i \quad (2)$$

When quantifying the size of route sets, we take route overlapping into consideration to enable comparison among travelers' route choices. We adopt the similarity coefficient SC_{kh} (Russo and Vitetta, 2003) to penalize the links shared by multiple routes in calculating the route diversity. Hence, with the number of reasonable routes R_{mn} , the route diversity D_{mn} for each O-D pair is calculated as:

1

$$D_{mn} = R_{mn} - \sum_{k \neq h \in K_{mn}} SC_{kh}, \forall m \neq n \in N \quad (3)$$

$$SC_{kh} = \frac{c_{kh}}{\sqrt{c_k c_h}}, \forall k \neq h \in K_{mn}, m \neq n \in N \quad (4)$$

2

3 where c_{kh} is the length of common links between routes k and h ; c_k and c_h are the lengths of
4 routes k and h , respectively; and K_{mn} is the set of reasonable routes for O-D pair (m, n) .

5

6 We aggregate the route diversity into the network level to enable the comparison of disruption
7 scenarios and extended networks. The aggregated route diversity is defined as the average of
8 the route diversity for all O-D pairs:

9

$$D_N = \frac{1}{|N|(|N|-1)} \sum_{m \neq n \in N} D_{mn}, \forall m \neq n \in N \quad (5)$$

10

11 Similarly, the performance of the network in terms of average travel time is:

12

$$T_N = \frac{1}{|N|(|N|-1)} \sum_{m \neq n \in N} T_{mn}, \forall m \neq n \in N \quad (6)$$

13

14 The detailed process of the solution algorithm for the aforementioned calculations is
15 summarized in Table 2.

16

17 **Table 2**

18 **Pseudocode for algorithm for network performance calculation**

Initialization: Input all nodes $\{m \in N\}$, all links $\{a \in A\}$, and the time cost matrix u

Procedure:

Step 1.1: obtain a reasonable adjacency matrix u_m

for $1 \leq m \leq |N|$ do

set $u_m = u$

for $1 \leq a \leq |A_m|$ do

Calculate the shortest route cost from origin r to head a_h and tail a_t with the Dijkstra algorithm

if $(1 + \tau_m^a)(c_m(a_h) - c_m(a_t)) \geq c_a, \forall a \in A_k$

then $u_m(a_t, a_h) = 0$

else

keep $u_m(a_t, a_h)$

end if

end for

Step 1.2: construct the route set K_{mn} by obtaining all possible routes from origin m to all nodes with u_m

$DFS(u_m, m)$

set S an empty stack

for $1 \leq j \leq |N|$ do

set visited $[j] = \text{false}$

push S, v

while S is not empty do

```

 $u = \text{pop } S$ 
if not visited  $[j]$ 
then visited  $[j] = \text{true}$ 
  for each unvisited neighbor  $i$  of  $j$ 
    push  $S, m$ 
  end for
end if
end while
end for
end  $DFS()$ 

Step 1.3a: calculate the number of reasonable routes  $R_{mn}$  for each O-D pair  $(m, n)$  using Eq. (1)
Step 1.3b: calculate the average travel time from  $m$  to all nodes  $n$ ,  $T_{mn}$  using Eq. (2)
Step 1.3c: calculate the similarity coefficient  $SC_{kh}$  and the route diversity  $D_{mn}$  from  $m$  to all nodes  $n$  using Eqs. (3-4)
end for
Step 2a: calculate the network-level route diversity  $D_N$  using Eq. (5)
Step 2b: calculate the network-level travel time  $T_N$  using Eq. (6)
outputs
  O-D-level performance index: route diversity  $D_{mn}$  and average travel time  $T_{mn}$ 
  Network-level performance index: route diversity  $D_N$  and average travel time  $T_N$ 

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4.3 Value of new development plans

The benefit of a network extension under normal operating conditions is evaluated as the difference in network performance between the extended and reference networks. Two indicators are used: route diversity D_N and average travel time T_N . A new line can serve as a complement (adding redundancy through route diversity) or a substitute (raising efficiency through reduced travel time) to other lines. Thus, the value of a network extension is first evaluated in terms of the overall impact on passengers. Additionally, a new line could benefit different groups of passengers in different ways (i.e., as a complement or substitute). Other than the measures that are computed at the network level, indicators defined at the O-D level (Eqs. (2)-(3)) allow investigating the spatial disparity of topological characteristics among O-D pairs. Cluster analysis is then applied to obtain classes of O-D pairs with the minimal within-group variance and maximal between-group variance. Two-step cluster analysis is performed here. The optimal number of clusters is based on a conventional approach with silhouette measures of cohesion and separation (Rousseeuw, 1987). A core principle is that disaggregated information can facilitate the investigation of the network topology by allowing one to compare statistical distributions across networks.

In parallel with cluster analysis, we perform the vulnerability analysis of each station to illuminate the variations between stations and identify the strategic importance of each station's served area. Conceptually, identifying vulnerable components and investigating their temporal evolution under different development projects can help cost-effective resource allocation to enhance the network's resiliency. Identifying critical elements is a standard assessment procedure in vulnerability analysis, which can effectively reveal the weaknesses of the network (Jiang et al., 2018; Mattsson and Jenelius, 2015; Xu et al., 2018b; Zhang et al., 2019).

When a station is closed, some passengers may be redirected to a smaller set of alternatives. Let N_C , N_D , $N_W \in N$ be the subsets of stations closed, stations disconnected from the major part of the network, and stations working after disruption of station r respectively. Explicitly, we focus on the scenarios with $N_D = 0$, so as to delve deeper into station areas including those that do not

lack travel alternatives. The nodal vulnerability V_r for station r is based on the overall impact of the disruption on the number of available routes, and defined as:

$$V_r = \frac{D_N(O) - D_N(r)}{D_N(O)}, \forall r \in N \quad (7)$$

where $D_N(O)$ and $D_N(r)$ are the network route diversity during normal operations and with closure of station r respectively.

Network expansion generally benefits passengers under both normal and disrupted conditions, in terms of shortening travel times and increasing route diversity. However, it does not necessarily benefit passengers to the same extent under both conditions, meaning that some areas may be more vulnerable to the impacts of disruptions. The value of a network expansion for individual station m under disrupted conditions is evaluated as the difference between the station's vulnerability during disruption in the extended network M^+ and the reference network M_0 :

$$U_{station,r}(\Delta M) = V_r \Delta \quad (8)$$

Considering the spatial variation of station vulnerability and disparate effects of the new lines, we focus on the following.

- (1). How the most vulnerable parts of the network are affected by the new expansions. Specifically, we focus on the 10 most vulnerable stations, which should be the top priority for reducing vulnerability.
- (2). How the topological effects (positive or negative, and their magnitude) of new expansions vary among different stations and the corresponding value they gain.

5. Value of New Lines Assessed with Route Diversity Measures

5.1 The value of new lines for network route diversity

We use the route diversity measures to assess the performance of the Hong Kong MTR network. These measures quantify the feasible routes available for travelers. More available routes correspond to more evacuation routes in the event of disaster. Hence, it is vital to provide multiple alternative routes, particularly for important O-D pairs with a large number of commuting trips, and for vulnerable stations. The network-level route diversity is first evaluated with the statistic of route availability distribution during normal operation. For the existing network, the proportion of all O-D pairs connected by only one reasonable route $P[1]$ is calculated as 0.587, and the network-level route diversity index is 1.116. The distribution of route diversity and travel time of O-D pairs is shown in Fig. 3. We find that the routes with the greatest route diversity (greater than 3) are from East Tsim Sha Tsui to Sham Shui Po and from Prince Edward to Austin. This is understandable given that these stations are located at the center and serve as a hub for local coverage. Many stations in the center form a grid pattern, which increases the number of alternatives. However, due to the high efficiency of the radial lines for trips between main urban and suburbs areas, the alternative routes provided by the circumferential lines are comparatively much less feasible. Trips originating or terminating in the outer city generally have fewer alternatives (i.e., lower route diversity). For example, trips between the northern and western parts of the New Territories, which on average require more than 60 minutes, are considered long journeys. The radial segments of the ERL and WRL

provide efficient routes for those O-D pairs. Although the circumferential segments provide alternative routes, they are not considered reasonable by Eq. (3). Therefore, while some O-D pairs enjoy higher route diversity (more choices), others offer a shorter travel time.

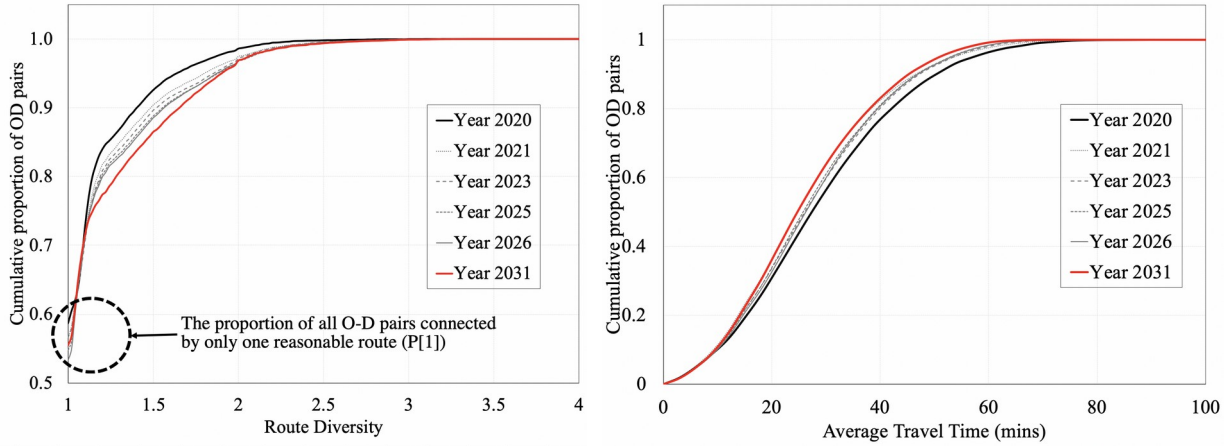


Fig. 3. (a) Cumulative distribution of route diversity and (b) average travel time of O-D pairs from 2019 to 2031

We further examine how the addition of new lines enhances the route redundancy by improving the route diversity and reducing travel time. Table 2 summarizes the extent of the planned MTR expansion from 2019 to 2021, 2023, 2025, 2026, and 2031. The cumulative frequency distributions of route diversity and travel time are presented in Fig. 3 to further illustrate the association between these two measures at the O-D level. The results reveal a gradual improvement of the network in terms of increasing route diversity (where lower cumulative proportions are preferable) and reducing travel time (where higher cumulative proportions are preferable). This tendency is more distinguishable in 2021 and 2031, suggesting that critical transitions occur in those years. The main reason for the considerable enhancement of route diversity is the completion of the SCL and NIL, which benefit the network topology due to their location in the inner city, so large numbers of existing trips can make use of the new lines. They also shorten some existing trips, as indicated by the significant drop in average travel time. Besides the SCL and NIL, the other new lines mostly offer a combination of network extension (i.e., extending its reach) and providing redundant alternatives for existing O-D trips. It is worth noting that the value of $P[1]$ slightly increases by 2031, suggesting that the NIL provides such an efficient choice that some O-D pairs rely exclusively on this line as the most reasonable route. The average travel time of the network increases slightly between 2021 and 2026 as the network is extended to nearby suburbs and stations are added to connect already existing stations. Overall, the route diversity continuously increases, while the average travel time decreases, as the network evolves.

5.2 The value of new lines for O-D-level route diversity

Although the results show an improvement of overall value as the network complexity increases over time, this does not necessarily imply that all users at the O-D level benefit from the new lines. Our assessment of the value of the new lines is therefore carried down to the O-D level, by evaluating the improvements in route availability and time saving for the O-D pairs. This investigation focuses on clusters of O-D pairs of the network over different time scales. The information is then used to identify the prominent network topologies that contribute to the route diversity. Three clusters of O-D pairs are identified (Table 3). Group A represents O-D pairs that are provided with faster routes owing to the network extension, identified by the

reduced average travel time and route diversity. Travelers in this group enjoy much faster journeys than before. As the new routes have much shorter travel times, the previous route sets in the old network become unattractive and disfavored. Group B represents O-D pairs for which the number of alternative routes increases. This group benefits from the new lines specifically from the route diversity perspective. Travelers perceive a new alternative route as an increase in utility, even if it does not provide significant time saving. Group C represents O-D pairs that are unaffected in terms of route diversity and travel time. This group derives no benefit from the new lines as they provide neither significant time saving nor additional reasonable routes between the O-D pairs.

The completion of the SCL in 2021 and NIL in 2031 has an obvious topological effect on the O-D pairs. The SCL provides a connection between two major areas in the New Territories that are served by large numbers of stations. The radial properties of this L-shaped line, which passes through the city center, contribute to travel time reduction between the inner and outer cities for 24.3% of O-D pairs. Due to the radial properties of the new line, its benefits spread indirectly to some other O-D pairs (a further 9.0%) by providing alternative routes. In comparison, the NIL makes a similar contribution, in terms of travel time reduction and alternative routes, to the O-D pairs. However, it acts more like a circumferential line in the main urban area to provide shorter connections between radial segments. The other lines, such as the NOL, EKL, and SILW, lie on the edge of the network topology. Their effects are more local than those of the SCL and NIL. Their topological effects on the network are limited, influencing less than 4% of O-D pairs. Overall, the route diversity measure captures the topological effects of the new lines differently from the conventional consideration of the path with the shortest travel time, quantitatively reflecting the advantages of the new lines in providing alternative routes.

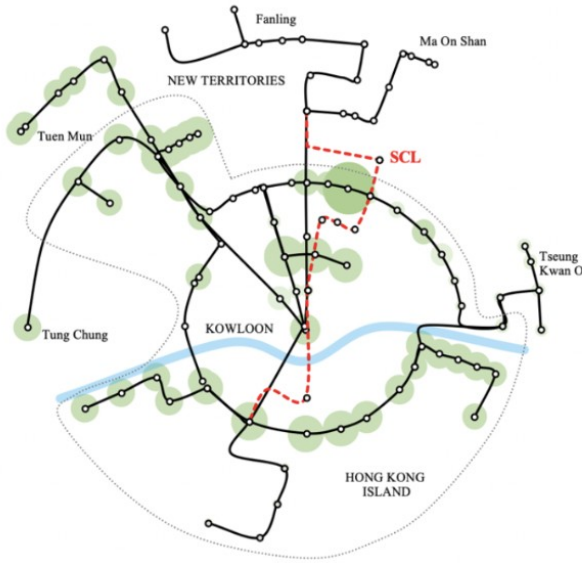
Table 3

Groups of O-D pairs identified in the evolution of the network from 2021 to 2031.

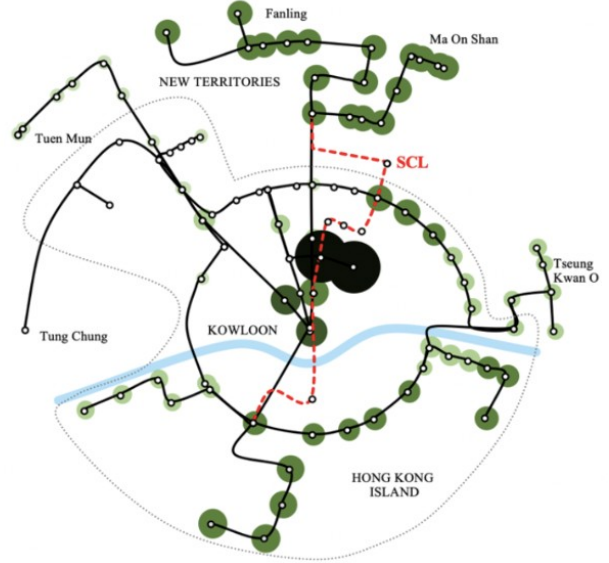
Group	A	B	C
Characteristics	O-D pairs provided with faster routes	O-D pairs provided with more alternatives	Unaffected O-D pairs
Year 2021 (SCL)			
Description			
Size	2810 (24.3%)	1036 (9.0%)	7709 (66.7%)
Route diversity	-0.16 (-0.09%)	+0.67 (+0.62%)	0.00 (0.00%)
Travel time (mins)	-5.37 (-0.16%)	-0.86 (-0.03%)	-0.08 (-0.00%)
Year 2023 (NOL)			
Description			
Size	299 (2.2%)	148 (1.1%)	12893 (96.6%)
Route diversity	-0.06 (-0.07%)	+0.89 (+0.45%)	0.00 (0.00%)
Travel time (mins)	-18.88 (-0.55%)	-0.50 (-0.01%)	-0.02 (-0.00%)
Year 2025 (EKL)			
Description			
Size	250 (1.7%)	274 (1.9%)	14238 (96.5%)
Route diversity	-0.25 (-0.26%)	+0.56 (+0.30%)	0.00 (0.00%)
Travel time (mins)	-5.74 (-0.17%)	-0.20 (-0.01%)	0.00 (0.00%)
Year 2026 (SILW)			
Description			
Size	12 (0.1%)	16 (0.1%)	16228 (99.8%)
Route diversity	-0.09 (-0.09%)	+0.34 (+0.16%)	0.00 (0.00%)
Travel time (mins)	-3.00 (-0.18%)	0.00 (0.00%)	0.00 (0.00%)
Year 2031 (NIL)			
Description			
Size	2365 (13.1%)	1249 (6.9%)	14476 (80.0%)
Route diversity	-0.25 (-0.25%)	+0.69 (+0.38%)	0.00 (0.00%)

Travel time (mins)	-6.02 (-0.24%)	-0.77 (-0.02%)	-0.11 (-0.00%)
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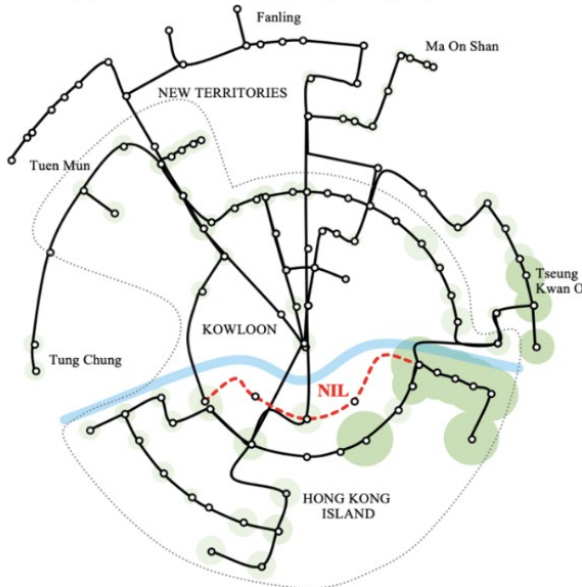
The spatial variation of the topological effects of the SCL and NIL, regarding the clusters of O-D pairs, is further illustrated in Fig. 4. Considering Group A, it is immediately clear that the existing ERL/MOL and WRL directly benefit from the SCL with respect to travel time. In the extended network, the MOL connects with the WRL in the city center while the ERL connects with the terminus of the extended MOL. However, unlike the ERL and MOL, the WRL not only benefits with respect to time saving but also increased route diversity for some O-D pairs. It is interesting to find that both ends of the new lines should gain the same topological benefit from the new expansion. Overall, the topological effect of the SCL is spread across the entire network. No part of the network receives a significantly larger or smaller share of the benefits, according to the evaluation of route diversity and travel-time saving. In contrast, upon the extension of the NIL, the eastern part of the network gains the most topological benefit in both travel-time saving and route diversity. Considering that the ERL and TCL connect directly to the NIL, it is surprising that neither benefits from the NIL in both respects at once. Rather, the ERL only benefits from travel-time saving while the TCL only benefits from the increased route diversity for a limited number of O-D pairs. Overall, the topological effect of the NIL is less evenly distributed among O-D pairs, although it does affect a significant percentage of O-D pairs according to the measures adopted here.



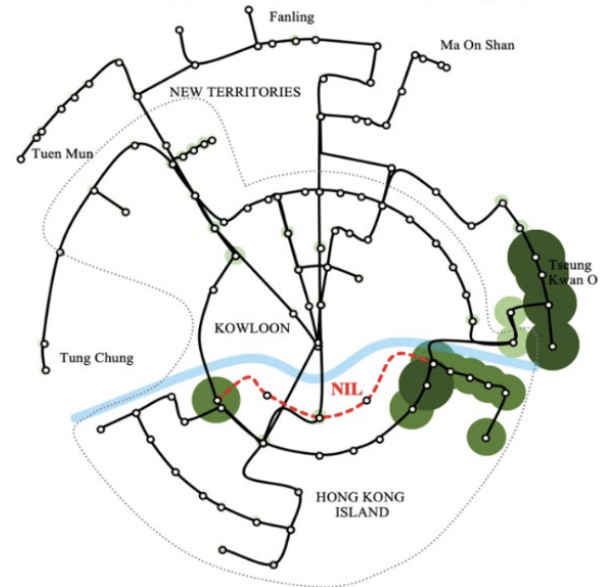
(a) SCL in Year 2021 (Group A)



(b) SCL in Year 2021 (Group B)



(c) NIL in Year 2031 (Group A)



(d) NIL in Year 2031 (Group B)

● <0.1% ● 0.1%–0.2% ● 0.2%–0.3% ● 0.3%–0.4% ● 0.4%–0.5% ● 0.5%–0.6% ● >0.6%

Fig. 4. Distribution of the effects on different O-D pairs after the construction of the SCL and NIL. Circles with deeper color and larger size indicate higher percentages of O-D pairs originating from or terminating at those stations.

5.3 The value of new lines for reducing nodal vulnerability

To further analyze the performance of the MTR network during adverse events, we use the route diversity measures as indicators to evaluate the vulnerability and identify critical stations during such incidents. We assume that each station is disrupted in turn and the vulnerability of each station is calculated with Eq. (7). As shown in Fig. 5 and Table 4, the identity of the 10 most vulnerable stations is straightforwardly intuitive, as nearly 80% of the vulnerable stations in the selected years are transfer stations in the main urban area. Such stations have more lines passing through and are typically considered as the most important. Many of the vulnerable stations are located on radial segments in the inner city, reflecting their importance as transfer

1 nodes to the circumferential lines. However, not all vulnerable stations are transfer stations.
2 This indicates that a station's location, in addition to its connectivity, may play a role in its
3 importance in a metro network. For example, Austin station, ranked 10th, is not a transfer
4 station, but is a close neighbor of East Tsim Sha Tsui (ranked 2nd) and is located on a radial
5 line connecting the center with the western part of the network. The overall results indicate that
6 the radial segments crucially serve as the backbone of the network but are vulnerable to
7 disruption due to poor route redundancy. For comparison, Wu et al. (2018) studied the MTR
8 network using the metric of betweenness centrality. Although they included some of the same
9 stations (e.g., Kowloon Tong and Prince Edward) in the top 10 list, some of the key stations in
10 the network were absent. For instance, in our study, Tsim Sha Tsui is ranked 3rd, reflecting its
11 role as a transfer station between the Tseun Wan Line (TWL) and WRL. Although the
12 relatively long transfer time reduces its importance according to centrality measures, which
13 focus on the shortest routes, its role as a transfer station increases the number of reasonable
14 routes for which it offers an alternative transfer option. When its transfer role is taken into
15 account, the topological advantages of this station emerge, as it can be considered an important
16 transfer node between two efficient radial lines. This highlights that the calculation of the
17 shortest path may not fully reflect the importance of transfer nodes in the network. As a result,
18 the proposed measures in this study, which integrate the characteristics of the travelers' route
19 choice preferences, are more useful. The route diversity measures in this study provide a more
20 comprehensive topological analysis by identifying vulnerable stations from the perspective of
21 travelers' route choices. When considering the locations that are most susceptible to disruption,
22 these vulnerable stations emerge as an essential focus for future expansion and reconstruction
23 projects.

24
25 The vulnerability of stations changes as the network is extended from 2019 through 2031. As
26 shown in Table 4, some stations are identified as vulnerable in multiple selected years but
27 ranked differently. For example, Admiralty becomes less vulnerable than East Tsim Sha Tsui in
28 2021, a reversal from 2019. The 10 most vulnerable stations, which are all located within Hong
29 Kong's urban area, provide information on the weakness of the metro network. For instance, in
30 2021, two vulnerable components (radial segments in the inner city) gain topological benefits
31 from the opening of the SCL, as indicated by the reduction in vulnerability shown in Fig. 5. The
32 extension of the ERL to Hong Kong Island offers transfer alternatives between the radial lines,
33 which reduces the vulnerability of Tsim Sha Tsui and East Tsim Sha Tsui. However, there are
34 still four vulnerable stations located on the radial segments of the ISL, indicating its high
35 vulnerability. Meanwhile, some stations remain on the list even after several expansions.
36 Transfer stations like Nam Cheong and Tsim Sha Tsui, for example, stay near the top of the list.
37 Admiralty, as a transfer hub, also remains high on the list, although its vulnerability is reduced
38 through the introduction of new lines. We highlight that Austin, despite being a non-transfer
39 station, remains vulnerable over time. These findings may imply blind spots in the planning
40 process. The rise of new vulnerable stations (Hong Kong, Kowloon, and Olympic) connecting
41 to the new line NIL should not be ignored in future planning.

Table 4

Trends in the ranking of station vulnerability in different phases of the proposed extensions.
Top 10 stations highlighted for each reference year.

Station	Year					
	2019	2021	2023	2025	2026	2031
<u>Transfer stations</u>						
Admiralty TWL	0.058 (1)	0.040 (6)	0.040 (7)	0.037 (8)	0.038 (7)	0.036 (9)
East Tsim Sha Tsui	0.057 (2)	0.048 (2)	0.052 (2)	0.049 (2)	0.047 (2)	0.051 (1)
Nam Cheong WRL	0.046 (6)	0.049 (1)	0.054 (1)	0.052 (1)	0.048 (1)	0.049 (2)
Tsim Sha Tsui	0.052 (3)	0.039 (8)	0.040 (8)	0.037 (7)	0.037 (8)	0.034 (13)
Admiralty ISL	0.037 (15)	0.045 (3)	0.045 (5)	0.041 (5)	0.039 (5)	0.036 (7)
Mei Foo WRL	0.148 (-)	0.140 (-)	0.049 (3)	0.045 (4)	0.045 (3)	0.047 (4)
Tsuen Wan West	0.127 (-)	0.120 (-)	0.042 (6)	0.039 (6)	0.039 (6)	0.046 (5)
Yau Ma Tei TWL	0.046 (4)	0.025 (19)	0.024 (23)	0.024 (28)	0.023 (29)	0.026 (29)
Kowloon Tong KTL	0.046 (5)	0.020 (37)	0.020 (42)	0.024 (26)	0.023 (28)	0.027 (22)
Nam Cheong TCL	0.045 (7)	0.028 (15)	0.029 (17)	0.029 (15)	0.028 (16)	0.034 (14)
Prince Edward KTL	0.042 (9)	0.022 (32)	0.022 (35)	0.025 (20)	0.024 (23)	0.026 (25)
North Point ISL	0.027 (26)	0.039 (10)	0.037 (14)	0.034 (12)	0.032 (12)	0.025 (37)
Hung Hom WRL	0.041 (11)	0.037 (12)	0.039 (10)	0.027 (18)	0.021 (37)	0.035 (12)
Hong Kong	0.020 (32)	0.025 (19)	0.026 (19)	0.025 (24)	0.025 (23)	0.040 (6)
<u>Non-transfer stations</u>						
Austin	0.041 (10)	0.044 (4)	0.048 (4)	0.046 (3)	0.044 (4)	0.049 (3)
Wan Chai	0.028 (23)	0.041 (5)	0.040 (9)	0.036 (9)	0.034 (9)	0.024 (40)
Causeway Bay	0.028 (24)	0.040 (7)	0.039 (11)	0.035 (10)	0.033 (10)	0.023 (52)
Jordan	0.044 (8)	0.024 (21)	0.023 (27)	0.023 (31)	0.022 (34)	0.025 (31)
Tin Hau	0.027 (25)	0.039 (9)	0.038 (12)	0.034 (11)	0.033 (11)	0.022 (54)
Kowloon	0.020 (33)	0.023 (25)	0.024 (24)	0.023 (33)	0.023 (31)	0.036 (8)
Olympic	0.021 (31)	0.022 (30)	0.023 (29)	0.022 (37)	0.022 (35)	0.036 (10)
Average vulnerability of top 10 stations	0.047	0.038	0.045	0.038	0.040	0.039

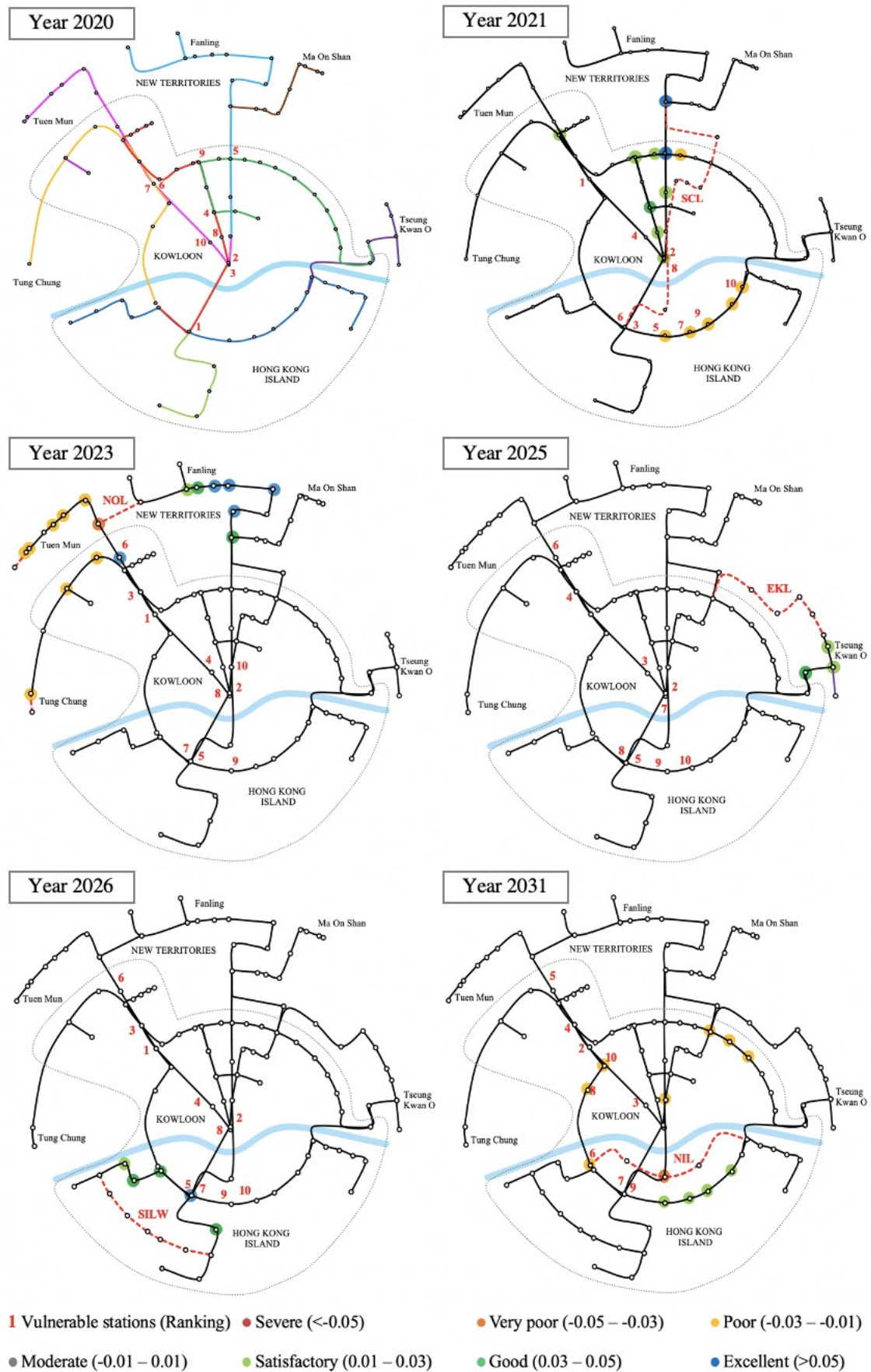


Fig. 5. Vulnerable stations and the value of new lines for reducing nodal vulnerability

With a view to improving network resilience, we would like to remedy the existing weaknesses by building new lines as long-term adaptive measures. Nevertheless, new lines do not afford equal improvements in all disruption scenarios, even though they always increase route diversity. In fact, the impacts of disruption are not consistently lower in the extended network than in the reference network in terms of the station vulnerability. Stations could be more vulnerable in the extended network for some cases because the new lines do not necessarily increase route diversity to the same extent during disruptions as under normal operating conditions. That is, the new lines cannot be fully utilized as an alternative travel route by passengers affected by disturbances. This implies that the value of redundancy of some new lines is negative for some scenarios. For instance, the SCL adds to the network several new vulnerable stations on the circumferential line on Hong Kong Island. The ultimate cause of high vulnerability is always a lack of rerouting alternatives in the case of disruption. It is not surprising that there is a lack of redundancy on Hong Kong Island. The rise of the vulnerability ranking of these stations shows the necessity of providing them with redundant routes. Inspection of the map of planned lines from 2019 to 2031 suggests that the NIL in 2031 could be a complementary solution to this problem. As shown in Fig. 5, the NIL brings about a topological benefit to the aforementioned segments by reducing their vulnerability. The NIL offers a bypass alternative parallel to the ISL, and rerouting possibilities for disruption scenarios. This evidence suggests the complementary ability of the NIL and the SCL to reduce each other's vulnerability and provide a more robust metro network. Hence, to determine whether the overall contribution of a new line is positive, the consequences in the event of its disruption have to be taken into consideration. The changes in station vulnerability thus have implications for the prioritization of future robustness investments and resource allocation.

6. Conclusion

In this paper, the spatio-temporal effects of the planned development of a metro network were investigated using a new network performance measure, route diversity, taking Hong Kong as the case study. The MTR network is expanding rapidly, which has gradually resulted in increasing route diversity and reduced travel time. However, this does not necessarily imply that all users benefit from the new lines. According to our calculations, route diversity will be continually improved by the new lines in the main urban area (SCL and NIL in 2021 and 2031, respectively) enabling more alternative possible routes for O-D trips. New lines outside the main urban area will complete the regular ring-radial network in the periphery, which previously only had radial lines. Using the route diversity measures, we obtained disaggregated information at the O-D level to reveal the disparate topological effects of different new lines. It was shown that O-D pairs exhibit differentiated patterns of improvement depending on their topologies in the network. On the basis of these projected benefits in terms of route diversity and travel time, the O-D pairs were divided into three clusters, allowing a fuller understanding of the situation after the new lines are built. Additionally, we studied the performance of the network in a disruption scenario to assess whether each new metro line will add to the redundancy of the system. By comparing the consequences of disruption in the expanded and current networks, our findings clearly show that the new lines will not lessen the consequences of disruption in all scenarios, but will sometimes exacerbate them. The evolution of the three distinct spatial patterns emphasizes the importance of matching the vulnerable parts of the existing network with the topological effects of new lines. By identifying the relative position of new lines in the local spatial structure, we can select and prioritize alternative expansions that increase redundancy for strategic planning. Moreover, the results reveal that the new lines will add new vulnerable stations into the network, although the effects of disruption will be reduced due to the route redundancy introduced by the new lines. It is vital to be aware of the

1 weak points introduced by new lines, as well as any blind spots in the planning process, to
2 make optimal use of the limited human, material, and financial resources to protect these
3 stations.

4
5 It should be noted that the results of this study are not universally applicable because each
6 transit system is developed based on the local context. As such, the analysis of Hong Kong,
7 which can be conceptualized as a circular city, may not be applicable to the evolution of metro
8 systems with different topologies. However, the finding that the topological benefits of a new
9 line spread across the network, rather than only favoring limited areas, is clear from earlier
10 research (Derrible, 2012). In this context, this study contributes to the literature in various ways.
11 First, route diversity, based on the concept of reasonable routes from travelers' perspective, is a
12 relatively new measure in transportation network studies. We examined the network
13 performance under both normal operations and disruption for the evolving Hong Kong MTR,
14 one of the most sophisticated public transit systems in the world, in the context of the city's
15 rail-based transit-oriented development. Second, we standardized the new measures for
16 longitudinal analysis and identified the areas that benefited more and less from network
17 extension in the context of route diversity. Finally, using new measures of route diversity
18 allows transportation policymakers and researchers an alternative view of the characteristics of
19 the public transit networks from travelers' perspective. As a future extension of this research,
20 the proposed analytical framework could be applied to other public transit systems for
21 comparative analysis. Furthermore, although route diversity measures, as well as vulnerability
22 analysis, provide vital information on the properties and development of urban rail transit
23 networks, research should be extended to the planners' perspective, which focuses on station
24 capacity and line capacity (Xu et al., 2018a). This research direction will be pursued when the
25 operational and scheduling data become available.

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2

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References

- Bono, F., Gutiérrez, E., 2011. A network-based analysis of the impact of structural damage on urban accessibility following a disaster: The case of the seismically damaged Port Au Prince and Carrefour urban road networks. *J. Transp. Geogr.* 19, 1443–1455. <https://doi.org/10.1016/j.jtrangeo.2011.08.002>
- Bruneau, M., Chang, S.E., Eguchi, R.T., Lee, G.C., O'Rourke, T.D., Reinhorn, A.M., Shinozuka, M., Tierney, K., Wallace, W.A., Von Winterfeldt, D., 2003. A framework to quantitatively assess and enhance the seismic resilience of communities. *Earthq. Spectra* 19, 733–752. <https://doi.org/10.1193/1.1623497>
- Cats, O., 2016. The robustness value of public transport development plans. *J. Transp. Geogr.* 51, 236–246. <https://doi.org/10.1016/j.jtrangeo.2016.01.011>
- Chen, S., Claramunt, C., Ray, C., 2014. A spatio-temporal modelling approach for the study of the connectivity and accessibility of the Guangzhou metropolitan network. *J. Transp. Geogr.* 36, 12–23. <https://doi.org/10.1016/j.jtrangeo.2014.02.006>
- Derrible, S., 2012. Network centrality of metro systems. *PLoS One* 7. <https://doi.org/10.1371/journal.pone.0040575>
- Faturechi, R., Miller-Hooks, E., 2014. A mathematical framework for quantifying and optimizing protective actions for civil infrastructure systems. *Comput. Civ. Infrastruct. Eng.* 29, 572–589. <https://doi.org/10.1111/mice.12027>
- Gao, L., Liu, X., Liu, Y., Wang, P., Deng, M., Zhu, Q., Li, H., 2019. Measuring road network topology vulnerability by Ricci curvature. *Phys. A Stat. Mech. Appl.* 527, 121071. <https://doi.org/10.1016/j.physa.2019.121071>
- Gu, Y., Fu, X., Liu, Z., Xu, X., Chen, A., 2020. Performance of transportation network under perturbations: Reliability, vulnerability, and resilience. *Transp. Res. Part E Logist. Transp. Rev.* 133, 1–16. <https://doi.org/10.1016/j.tre.2019.11.003>
- Hawas, Y.E., Hassan, M.N., Abulibdeh, A., 2016. A multi-criteria approach of assessing public transport accessibility at a strategic level. *J. Transp. Geogr.* 57, 19–34. <https://doi.org/10.1016/j.jtrangeo.2016.09.011>
- Hong, L., Yan, Y., Ouyang, M., Tian, H., He, X., 2017. Vulnerability effects of passengers' intermodal transfer distance preference and subway expansion on complementary urban public transportation systems. *Reliab. Eng. Syst. Saf.* 158, 58–72. <https://doi.org/10.1016/j.ress.2016.10.001>
- Jenelius, E., Cats, O., 2015. The value of new public transport links for network robustness and redundancy. *Transp. A Transp. Sci.* 11, 819–835. <https://doi.org/10.1080/23249935.2015.1087232>
- Jiang, R., Lu, Q.C., Peng, Z.R., 2018. A station-based rail transit network vulnerability measure considering land use dependency. *J. Transp. Geogr.* 66, 10–18. <https://doi.org/10.1016/j.jtrangeo.2017.09.009>
- Jing, W., Xu, X., Pu, Y., 2019. Route redundancy-based network topology measure of metro networks. *J. Adv. Transp.* 2019, 4576961. <https://doi.org/10.1155/2019/4576961>
- Kim, H., Song, Y., 2015. Examining accessibility and reliability in the evolution of subway systems. *J. Public Transp.* 18, 89–106. <https://doi.org/10.5038/2375-0901.18.3.6>

1 Leurent, F.M., 1997. Curbing the computational difficulty of the logit equilibrium assignment
2 model. *Transp. Res. Part B Methodol.* 31, 315–326. <https://doi.org/10.1016/s0191->
3 2615(96)00035-5

4 Liu, W., Li, X., Liu, T., Liu, B., 2019. Approximating betweenness centrality to identify key
5 nodes in a weighted urban complex transportation network. *J. Adv. Transp.* 2019, 9024745.
6 <https://doi.org/10.1155/2019/9024745>

7 Loo, B.P.Y., 2009. How would people respond to a new railway extension? The value of
8 questionnaire surveys. *Habitat Int.* 33, 1–9. <https://doi.org/10.1016/j.habitatint.2008.02.002>

9 Loo, B.P.Y., Chen, C., Chan, E.T.H., 2010. Rail-based transit-oriented development: Lessons
10 from New York City and Hong Kong. *Landsc. Urban Plan.* 97, 202–212.
11 <https://doi.org/10.1016/j.landurbplan.2010.06.002>

12 Loo, B.P.Y., Leung, K.Y.K., 2017. Transport resilience: The Occupy Central Movement in
13 Hong Kong from another perspective. *Transp. Res. Part A Policy Pract.* 106, 100–115.
14 <https://doi.org/10.1016/j.tra.2017.09.003>

15 López, F.A., Páez, A., Carrasco, J.A., Ruminot, N.A., 2017. Vulnerability of nodes under
16 controlled network topology and flow autocorrelation conditions. *J. Transp. Geogr.* 59, 77–87.
17 <https://doi.org/10.1016/j.jtrangeo.2017.02.002>

18 Lordan, O., Sallan, J.M., Simo, P., 2014. Study of the topology and robustness of airline route
19 networks from the complex network approach: A survey and research agenda. *J. Transp. Geogr.*
20 37, 112–120. <https://doi.org/10.1016/j.jtrangeo.2014.04.015>

21 Lu, Q.C., Zhang, J., Peng, Z.R., Rahman, A.S., 2014. Inter-city travel behaviour adaptation to
22 extreme weather events. *J. Transp. Geogr.* 41, 148–153.
23 <https://doi.org/10.1016/j.jtrangeo.2014.08.016>

24 Luo, D., Cats, O., van Lint, H., Currie, G., 2019. Integrating network science and public
25 transport accessibility analysis for comparative assessment. *J. Transp. Geogr.* 80, 102505.
26 <https://doi.org/10.1016/j.jtrangeo.2019.102505>

27 Mattsson, L.G., Jenelius, E., 2015. Vulnerability and resilience of transport systems - A
28 discussion of recent research. *Transp. Res. Part A Policy Pract.* 81, 16–34.
29 <https://doi.org/10.1016/j.tra.2015.06.002>

30 Mejia-Dorantes, L., Paez, A., Vassallo, J.M., 2012. Transportation infrastructure impacts on
31 firm location: The effect of a new metro line in the suburbs of Madrid. *J. Transp. Geogr.* 22,
32 236–250. <https://doi.org/10.1016/j.jtrangeo.2011.09.006>

33 Nian, G., Chen, F., Li, Z., Zhu, Y., Sun, D., 2019. Evaluating the alignment of new metro line
34 considering network vulnerability with passenger ridership. *Transp. A Transp. Sci.* 15, 1402–
35 1418. <https://doi.org/10.1080/23249935.2019.1599080>

36 Parkes, S.D., Jopson, A., Marsden, G., 2016. Understanding travel behaviour change during
37 mega-events: Lessons from the London 2012 Games. *Transp. Res. Part A Policy Pract.* 92,
38 104–119. <https://doi.org/10.1016/j.tra.2016.07.006>

39 Roberts, M.J., Newton, E.J., Canals, M., 2016. Radi(c)al departures: Comparing conventional
40 octolinear versus concentric circles schematic maps for the Berlin U-Bahn/S-Bahn networks
41 using objective and subjective measures of effectiveness. *Inf. Des. J.* 22, 92–115.
42 <https://doi.org/10.1075/idj.22.2.04rob>

- 1 Rodríguez-Núñez, E., García-Palomares, J.C., 2014. Measuring the vulnerability of public
2 transport networks. *J. Transp. Geogr.* 35, 50–63. <https://doi.org/10.1016/j.jtrangeo.2014.01.008>
- 3 Rousseeuw, P.J., 1987. Silhouettes: A graphical aid to the interpretation and validation of
4 cluster analysis. *J. Comput. Appl. Math.* 20, 53–65. [https://doi.org/10.1016/0377-](https://doi.org/10.1016/0377-0427(87)90125-7)
5 [0427\(87\)90125-7](https://doi.org/10.1016/0377-0427(87)90125-7)
- 6 RTHK News, 2019a. Admiralty station closed as police issue warning. [Rthk.hk](http://rthk.hk).
- 7 RTHK News, 2019b. Train derails at Hung Hom Station. [Rthk.hk](http://rthk.hk).
- 8 Russo, F., Vitetta, A., 2003. An assignment model with modified Logit, which obviates
9 enumeration and overlapping problems. *Transportation (Amst)*. 30, 177–201.
10 <https://doi.org/10.1023/A:1022598404823>
- 11 Sarlas, G., Páez, A., Axhausen, K.W., 2020. Betweenness-accessibility: Estimating impacts of
12 accessibility on networks. *J. Transp. Geogr.* 84, 102680.
13 <https://doi.org/10.1016/j.jtrangeo.2020.102680>
- 14 Song, Y., Kim, H., Lee, K., Ahn, K., 2018. Subway network expansion and transit equity?: A
15 case study of Gwangju metropolitan area, South Korea. *Transp. Policy* 72, 148–158.
16 <https://doi.org/10.1016/j.tranpol.2018.08.007>
- 17 Sun, D., Zhao, Y., LU, Q.C., 2015. Vulnerability analysis of urban rail transit networks: A case
18 study of Shanghai, China. *Sustain.* 7, 6919–6936. <https://doi.org/10.3390/su7066919>
- 19 Tagliacozzo, F., Pirzio, F., 1973. Assignment models and urban path selection criteria: Results
20 of a survey of the behaviour of road users. *Transp. Res.* 7, 313–329.
21 [https://doi.org/10.1016/0041-1647\(73\)90020-8](https://doi.org/10.1016/0041-1647(73)90020-8)
- 22 Tan, R., He, Q., Zhou, K., Xie, P., 2019. The effect of new metro stations on local land use and
23 housing prices: The case of Wuhan, China. *J. Transp. Geogr.* 79, 102488.
24 <https://doi.org/10.1016/j.jtrangeo.2019.102488>
- 25 Transport and Housing Bureau, 2014. Railway Development Strategy 2014, Hong Kong
26 Government Logistics Department. <https://doi.org/10.1017/CBO9781107415324.004>
- 27 Transport Department, 2019. Annual Transport Digest 2019.
- 28 Wan, C., Yang, Z., Zhang, D., Yan, X., Fan, S., 2018. Resilience in transportation systems: a
29 systematic review and future directions. *Transp. Rev.* 38, 479–498.
30 <https://doi.org/10.1080/01441647.2017.1383532>
- 31 Wang, J., Mo, H., Wang, F., 2014. Evolution of air transport network of China 1930-2012. *J.*
32 *Transp. Geogr.* 40, 145–158. <https://doi.org/10.1016/j.jtrangeo.2014.02.002>
- 33 Weckström, C., Kujala, R., Mladenovi, M.N., Saramäki, J., 2019. Assessment of large-scale
34 transitions in public transport networks using open timetable data: case of Helsinki metro
35 extension. *J. Transp. Geogr.* 79, 102470. <https://doi.org/10.1016/j.jtrangeo.2019.102470>
- 36 Wu, X., Dong, H., Tse, C.K., Ho, I.W.H., Lau, F.C.M., 2018. Analysis of metro network
37 performance from a complex network perspective. *Phys. A Stat. Mech. Appl.* 492, 553–563.
38 <https://doi.org/10.1016/j.physa.2017.08.074>
- 39 Xiao, X.M., Jia, L.M., Wang, Y.H., Zhang, C., 2019. Topological characteristics of metro
40 networks based on transfer constraint. *Phys. A Stat. Mech. Appl.* 532, 121811.
41 <https://doi.org/10.1016/j.physa.2019.121811>

- 1 Xu, X., Chen, A., Jansuwan, S., Yang, C., Ryu, S., 2018a. Transportation network redundancy:
2 Complementary measures and computational methods. *Transp. Res. Part B Methodol.* 114, 68–
3 85. <https://doi.org/10.1016/j.trb.2018.05.014>
- 4 Xu, X., Chen, A., Yang, C., 2018b. An optimization approach for deriving upper and lower
5 bounds of transportation network vulnerability under simultaneous disruptions of multiple
6 links. *Transp. Res. Part C Emerg. Technol.* 94, 338–353.
7 <https://doi.org/10.1016/j.trc.2017.08.015>
- 8 Zhang, X., Miller-Hooks, E., Denny, K., 2015. Assessing the role of network topology in
9 transportation network resilience. *J. Transp. Geogr.* 46, 35–45.
10 <https://doi.org/10.1016/j.jtrangeo.2015.05.006>
- 11 Zhang, Y., Marshall, S., Manley, E., 2019. Network criticality and the node-place-design
12 model: Classifying metro station areas in Greater London. *J. Transp. Geogr.* 79, 102485. <https://doi.org/10.1016/j.jtrangeo.2019.102485>
- 14 Zhu, Y., Wang, Z., Chen, P., 2018. Planning for operation: Can line extension planning mitigate
15 capacity mismatch on an existing rail network?. *J. Adv. Transp.* 2018, 1675967. <https://doi.org/10.1155/2018/1675967>
16