Planning Urban Ring Rail Transit Lines: A Case Study of Shanghai, China

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Reviewing Committee: AP065 - Rail Transit Systems
In response to the call for a paper on Rail Transit Congestion Monitoring and Management

Transportation Research Board’s 95th Annual Meeting, Washington DC, USA
ABSTRACT

Shanghai has the largest metro system in the world with a network length of more than 550 kilometers. Both Shanghai and Beijing are in the top five cities in terms of ridership, and some of the most important components of their metro systems are the ring transit lines. Many other cities, in China and elsewhere, also envision a ring transit line for their future rail transit networks. Using a previously developed analytical model for the long-range planning of ring transit lines, we compare the current alignment of the Shanghai ring line with the optimized model output, and recommend a potential second ring transit line for the future Shanghai network. Our findings suggest that the alignment of an existing ring line will impact the optimal alignment of the second ring line. In addition, if an outer ring line exists (or is planned to be constructed), the optimal location of the inner ring line may change. Furthermore, a sensitivity analysis was conducted to test the impact of changes on demand, value of time, and passenger ride cost on the second ring line. Zones that obtain the greatest benefit from introducing the second ring line were also determined. While we present a case study of Shanghai ring lines; the outcomes provide useful information for cities that are considering the expansion of their transit network with a first or second ring line. Unlike simulations and agent-based models, our model is easily transferable to any transit network.

Keywords: ring transit line; circumferential transit line; Shanghai
INTRODUCTION

Following decades of dependency on personal automobiles and planning for the use of personal vehicles as the main means of transportation, public transit has recently experienced growing attention. Increased travel and traffic congestion; increased cost of car ownership, operation, and parking; and environmental concerns and sustainability issues have shifted the focus of city planners and politicians towards public transportation. In addition, this trend is also occurring in society in general. Similar to when mass transit systems were first introduced approximately 150 years ago, public transit is now the primary method of transportation within many cities, especially in large cities in Asia and Europe; the trend is also true in some North American cities.

Due to the heightened demand for public transportation, cities in China have become leaders in planning and constructing metro systems; twenty-two cities have metro networks, and additional sixteen cities with metro systems currently under construction (1). Of these, Shanghai has the largest metro system, spanning more than 550 kilometers, and the system has only been in operation since 1993. Despite the large size of the Shanghai system, Beijing has a higher metro ridership. Both cities possess ring transit lines, and these lines are an important constituent of their metro systems; many other Chinese cities envision a ring transit line as a long-term transit network, including Chengdu (2), Harbin (3), Ningbo (4), as well as a semi-ring line in Shenzhen (5) and Chongqing (6).

In a purely radial rail network, destinations away from the city center can only be reached by travelling along the radial lines that pass through the center. Therefore, this network can result in unnecessary passenger loads for some corridors, high transfer loads in the city center, and additional distance, travel time, and transfers for passengers travelling across the city. A ring line provides better connectivity and decreases network vulnerability since there are alternative routes to each destination. Kennedy and Derrible (7), Yi and Chao (8), and Laporte et al. (9) showed that a ring or circumferential transit line greatly improves network connectivity, directness, and operational efficiency. Saidi, Wirasinghe, and Kattan (10) performed a review of rail transit networks globally with special emphasis on cities with ring transit lines. They found relationships between transit ridership and different city parameters, such as population, city area, and population density. Moreover, they also reviewed cities with rail ring transit lines, such as London, Moscow, Berlin, Beijing, Tokyo, and Shanghai. Population density and network length were found to be statistically significant parameters that warrant a ring line. Therefore, a city should have a high population density spread throughout the city rather than a densely populated single area to justify building a ring transit line. In addition, transit networks should first possess some radial lines and a certain level of network maturity before a ring transit line is introduced.

Ring lines are positioned around a city center and intersect radial lines to create transfer opportunities; and, thus, they support an integrated multipath network. In addition to saving passenger travel and wait times, increasing transit network connectivity and reliability, and reducing the transit load in the downtown core, ring lines also have the potential to increase the accessibility and development of new satellite centers. Vuchic (11) lists three important functions of ring lines: 1) improving connectivity among radial lines and distributing the
congestion away from radial lines in the Central Business District (CBD); 2) making trips between radial lines shorter by bypassing the CBD; and 3) serving the busy areas in a ring around the CBD.

Based on our observations of the Beijing and Shanghai metro ring lines, a ring line has other characteristics in addition to Vuchic’s list. First, a ring line provides coverage to areas not well serviced by the mass transit system. Also, ring lines allow for a high number of transfers relative to radial lines, as observed in the inner Beijing ring line and the Shanghai ring line. While radial lines primarily connect the CBD and major attraction or employment centers along the transit corridor to the residential areas, a ring line has several intersecting radial lines, providing more transfer opportunities. Therefore, a ring line has a higher ratio of transfers and a higher number of boarding and disembarking passengers with respect to through passengers. In addition, for cities with more than one ring line (an inner and outer ring with the same center), the defining characteristic of each line can be based on different factors. For example, the Beijing inner ring (Line 2) surrounds the high density CBD and is characterized by a high transfer load, whereas the outer ring (Line 10) provides coverage to passengers who are distant from the radial lines.

Some cities with ring line networks have built, or are planning to build, additional ring lines. Beijing currently has two full ring lines surrounding the CBD, making the connections between lines easier and more convenient, while also providing cross-town transit corridors within the network. The second (Line 10) was completed in 2013 (12). In addition, Paris is currently building a second ring line on the outskirts of the city with an expected completion in 2025 (13). Moscow expects its second ring line to be completed by 2018 (14). Shanghai is also planning the construction of a second ring transit line as a long-term plan (15). With the high level of recent attention being paid to ring transit lines, the main questions that arise are the following: when and where should a ring line (if any) be developed in a metro network? If it is feasible to build a ring line, what is the best alignment of the ring line? Is it possible to have more than one ring line, and how could a second ring line impact the optimum alignment of the first ring line?

In this paper, we analyze the Shanghai metro system using a ring-radial rail transit model developed by Saidi, Wirasinghe, and Kattan (16) to compare the current alignment of the first ring line in Shanghai with the model output and to investigate the possible location of a second ring line. The model is used to estimate the total passenger benefit of introducing a ring line, for example, improving access to the nearest rail transit line, decreasing ride times, and reducing the disutility that passengers will experience with transfers. The total capital and operating cost versus total passenger benefit are the components of an optimization model with the radius of the single ring line as the variable. The model uses origin destination (OD) data, a metro network structure, passenger cost factors (access cost, ride cost, wait cost, transfer penalty, and operation), and capital cost of the metro as the input. For the purpose of this paper, the model is extended to allow a second ring line to be tested for Shanghai.
OVERVIEW OF SHANGHAI METRO SYSTEM

The largest metro system in the world opened its first metro line in 1993, making Shanghai the third city in Mainland China, after Beijing and Tianjin, to have a rail rapid transit system. Since then, the Shanghai metro has become one of the fastest growing networks in the world with several lines currently under construction. Figure 1 shows the development of the Shanghai metro system over time. This growth has stemmed from the extremely high usage that the system regularly experiences. As of January 2014, in a normal weekday over 8 million passengers use the Shanghai metro; Shanghai set a ‘daily total number of boarding’ record of 10.28 million on September 25, 2015 (17).

The idea of building a metro line in Shanghai was first proposed in August 1956 as a military defense measure, and a preliminary plan originated for building an underground tunnel. Two lines were initially planned: Line 1 from north to south, and Line 2 from east to west. The actual construction of the metro lines in Shanghai commenced more than 30 years later in 1990. The first section of metro Line 1 was completed in 1993, and construction of Line 2 began in 1995. Line 2 now plays a vital role in the west-east corridor (18) as it connects the major airports in Shanghai: Hongqiao (mostly a domestic airport) and Pudong International Airport. In addition, the Century Avenue station is located on this line, and this station connects with three other lines (4, 6, and 9). Due to the extremely high demand for boarding and alighting, there are special regulations for passengers during peak hours to control crowding at this station in particular. The availability of the old railway line in Shanghai that connected the Shanghai Railway station to the city of Hangzhou reduced the required investment and construction time for Line 3. Lines 3 and 4 share the track for almost half of the ring, and construction of these lines commenced in 1997 and 2005, respectively (19).

The Shanghai ring line (Line 4) was originally planned to be longer (36 km vs. the current 33 km line), but with the high cost of construction and the savings from the partly shared track with Line 3, the original plan was changed to the current system. Further, the alignment of the Shanghai ring line follows, in part, underneath the alignment of the Shanghai inner ring road (20). Currently, one of the major problems with the shared track is maintaining appropriate headway. The headway on different sections of the ring corridor is not uniform, and this situation creates additional wait times and passenger overflow. Therefore, the Shanghai metro is planning to change the current operation of Line 3 so that it will only operate on the north section up to the ring corridor, but not on the ring corridor itself. In this way, the headway on the ring corridor will be uniform, but passengers from the north part of Line 3 will be required to transfer to Line 4 at Baoshan Road station. (20)

Line 5 was the first light rail transit line introduced in Shanghai (21); it begins at the final station of Line 1 at Xinzhuang and extends further south. Line 8 is another major line in Shanghai because the People’s Square, (the central station at the heart of Shanghai), the Shanghai Expo area, and other major attractions in the city are easily accessible from this line. It connects the Yangpu district to the downtown core, and mitigates the traffic pressure in the downtown area. Line 10 opened in 2010, and is the first autonomous line in China, operating without a driver (22). Furthermore, the Shanghai metro introduced the first line, Line 11, that
crosses two provinces (Shanghai and Jiangsu) in China, and in the future, this line will also be connected to Line S1 in Suzhou (23).
The Shanghai metro currently boasts a total of 14 lines, 337 stations, and 548 km of rail line, making it the most extensive metro network in the world, but, in terms of ridership, after Beijing and is on par with Seoul and Moscow(1). As the Shanghai metro continues to expand, it is expected that by 2020 six more lines will be constructed.

To conduct a cost-benefit analysis and optimize the alignment of the ring lines in Shanghai, we should use transportation or land use zonal OD data for an accurate and realistic analysis. However, due to the limited ability to access such data for Shanghai, we used peak period metro station OD data for a typical workday in 2013, and the 2013 network for the analysis. Total OD demand is 3.6 million per day for 263 zones; some zones produce as high as 60,000 and some as low as 1,000 trips. The average demand produced is 13,637 trips with a standard deviation of 11,686. For the purpose of data validation, we obtained the number of cell phone users for different areas throughout Shanghai during a typical workday in 2015. Metro lines other than the ring lines are assumed to be straight and are modeled as radial lines merging at the CBD, or are connected to another radial line via a diametrical line. The actual location of the stations and the current metro network were obtained in polar coordinates. Using this data and coding the radial and ring line of the Shanghai network, we assumed the radial lines to be linear and the ring line to be circular. We removed information for two lines (one whole line and half of another line), as they could not be coded as radial nor as a full ring line on the developed ring-radial model. We analyzed the Shanghai metro network to address the following questions:

- Assuming that the current Shanghai metro had no ring line, what would be the best alignment of a ring line in Shanghai? The result found from the model can be compared with the current ring line in Shanghai.
- Assuming Shanghai’s current metro network with the ring line, what is the optimal alignment of a second ring line? Will such a line be beneficial when compared to the cost of construction and operation?

The costs of constructing a metro line in different cities in China ranges from 500 million CNY (75 million USD) per kilometer in Shanghai (24) up to 800 million CNY (120 million USD) and, in some cases, 1 billion CNY (150 million USD) per kilometer for one of the newest metro lines in Xi’an (25). Since such an investment will be used for many years, we should calculate the investment for the annual or daily benefits of having a metro line. Shang and Zhang analyzed the operating cost of the Shanghai and Hangzhou metro systems by considering different factors, such as wages, maintenance fees, business cost, taxes, and surcharges (26). According to this study, the cost of the Shanghai metro operation is approximately 5.7 billion Yuan per year, or 12 million CNY (1.8 million USD) per kilometer per year. To estimate the average passenger access cost to the metro stations, we determined the composition of different access modes for the Shanghai metro. Pan et al. (27) investigated the average mode share of passenger access to, or egress from, a metro station in Shanghai. Different modes were considered, and the average percentages for access and egress modes, respectively, were estimated as follows: walk (51%, 81%), bus (29%, 13%), bike (11%, 1%), motorcycle (6%, 1%), and car (3%, 4%). Using the average speed of the different modes in Shanghai based on the fifth travel survey conducted by the Shanghai City Comprehensive Transportation Planning Institute (28), we were able to calculate the average speed of access/egress and metro ride for passengers. Value of time is also important for this analysis to estimate passenger ride and wait costs. The

TRB 2016 Annual Meeting  Paper revised from original submittal.
average value of time in Chinese cities, as reported in the literature, varies from 9 to 34 Yuan/hr (1.35 to 5.1 $/hr.) (29). In a study conducted by Guan (30), a median value of time of 24.6 Yuan/hr. (3.7 $/hr.) was found for large-scale residential areas in Shanghai. In another study, a value of time of 9.67 Yuan/hr. (1.5 $/hr.) was determined for metro transit users in Tianjin (31). Therefore, we employed a value of time of 20 Yuan/hr. (or 3 $/hr.) for this study, but we also tested different values as part of the sensitivity analysis. We used a transfer disutility of 2.17 Yuan/passenger (0.33 $/passenger) for the Shanghai metro system based on the information provided in (32). Table 1 displays the unit costs used in this study.

**MODEL DESCRIPTION**

Depending on the type of planning and optimization, we can assume a network with no ring line and add the operator’s cost of having one ring line (optimization for the first ring line in Shanghai). Alternatively, we can assume a network with one ring line and find the optimum alignment and the cost-benefit analysis of extending the network with a second ring line. Thus, the difference between these two scenarios provides the total passenger benefit with the addition of a ring line. The total passenger benefit is a function of the radius R. As the radius of the ring line changes, the total benefit to the passenger changes.

\[
Total \text{ Passenger Benefit}(R) = Total \text{ Passenger Cost for Current Transit Network} - Total \text{ Passenger Cost with Extended Transit Network}(R)
\]

(1)

The optimization problem is the operator’s cost minus the total passenger benefit of introducing the new ring line. The total operator’s cost includes the operating cost of the potential ring line and the capital cost of constructing the line. Both factors are a function of the radius of the ring line:

\[
Total Cost (R) = Operator’s Cost (R) - Total Passenger Benefit(R)
\]

(2)

The values with a negative total cost means that there are overall benefits to building a ring line. The radius with a minimum total cost displays the optimum location of the ring line.

Total passenger cost is calculated based on OD demand and the passenger cost for each OD pair. Multiplying these two matrices determines the total passenger cost for the entire network. We can run the multiplication for scenarios where a ring line exists or does not exist. Thus, we have the following:

\[
Total \text{ Passenger Cost for Extended Transit Network}(R) = \sum_{i,j}^{N} (PC(R)_{i,j}^{\min} * OD_{i,j})
\]

(3)

\[
Total \text{ Passenger Cost for Current Network} = \sum_{i,j}^{N} (PC_{i,j}^{\min} * OD_{i,j})
\]

(4)

where \(PC(R)_{i,j}^{\min}\) is the minimum passenger cost for zone i to zone j for an extended network with a ring line at radius R; \(PC_{i,j}^{\min}\) is the minimum passenger cost from zone i to zone j for the current network; and \(OD_{i,j}\) is the transit demand from zone i to zone j.
The minimum passenger cost for each OD pair is obtained by considering different passenger route choices for each OD pair. Readers are referred to (15) for additional details of a passenger route choice model for a single ring line. The model is extended to allow a second ring line in the paper. We assume a rail transit network with only two types of lines: radial and ring lines. Radial lines connect the CBD to the edges of the city, with some connecting to other radial lines at the CBD, forming a diametrical line. Therefore, passengers can either take the same line, without transferring, to travel to another side of the network, or they may have to transfer in the CBD and take another radial line. The ring-radial model (15) uses OD data input to depict a realistic travel pattern, as travel demands are not necessarily uniformly distributed or follow a particular continuous function as assumed in (33-35). Having a combination of many radial lines and two ring lines creates different route choices. Passengers will choose an alternative route with a minimum total travel cost. Different route alternatives in the ring-radial model are listed below:

1. Direct access from a given origin to a given destination without using the metro network.
2. Use only a radial line:
   2.1 Access the nearest radial line, take the radial line, access destination (1 wait cost);
   2.2 Access the nearest radial line, take the radial line, access destination; if needed transfer to another radial line in the CBD, or direct access to the destination (either 1 wait cost, or 2 wait costs and 1 transfer); and
   2.3 Direct access to the CBD and then take the radial line, access the destination (1 wait cost).
3. Use one ring line (radial line may also be used).
   3.1 Access the ring line, take the ring line, access destination (1 wait cost);
   3.2 Access the ring line, take the ring line, transfer to a radial line, access destination; if needed transfer to another radial line in the CBD, or direct access to destination from CBD (either 2 wait costs and 1 transfer, or 3 wait costs and 2 transfers);
   3.3 Access the nearest radial line, take the radial line, transfer to a ring line, access destination (2 wait costs and 1 transfer);
   3.4 Access the nearest radial line, take the radial line, transfer to a ring line, transfer to another radial line, access destination (3 wait costs and 2 transfers); and
   3.5 Direct access to the CBD, take radial line, transfer to a ring line, take the ring line, access destination (2 wait costs and, 1 transfer).
4. Use both ring lines (a radial line may also be used).
   4.1 Access a ring line, take the ring line, transfer to a radial line, if needed transfer to another radial line in the CBD, transfer to the other ring line, access destination (3 wait cost, 2 transfers or 4 wait cost, 3 transfers);
   4.2 Access a ring line, take the ring line, transfer to a radial line, transfer to another ring line, transfer to another radial line, access destination (4 wait cost, 3 transfers);
   4.3 Access a radial line, take the radial line, transfer to a ring line, take the ring line, transfer to another radial line, take the radial line, access destination (4 wait costs and 3 transfers);
Alternatives 4.1, 4.2, and 4.3 are unlikely to be the options with the minimum passenger cost. The main changes to the total passenger cost for different route alternatives occur for alternative 3, where for each OD pair, one of the ring lines can be in the route with the minimum passenger cost.

We used the deterministic passenger route choice model to calculate passenger costs for different route options for each OD pair. The passenger route choice model calculates the minimum cost option for each of the different available routes. The model then uses the passenger cost of each route, with the minimum cost for each OD pair, for alternatives with a ring line or no ring line in place. The general passenger cost equations for the above alternatives are:

**Direct Access Alternative:**  
\[ y_a(D) \]  
(5)

**Radial Line Alternative:**  
\[ y_aD_o + y_aD_d + \zeta_{RL}kH_{RL}y_w + (\zeta_{RL} - 1)y_T + y_RD_R \]  
(6)

**Ring Line Alternative:**  
\[ y_aD_o + y_aD_d + \zeta_{RN}kH_{RN}y_w + \zeta_{RL}kH_{RL}y_w + (\zeta_{RL} + \zeta_{RN} - 1)y_T + y_RD_R \]  
(7)

where:
- \( y_a \) is the generalized access cost to reach the destination or rail line per kilometer per passenger;
- \( y_w \) is the wait cost per hour per passenger;
- \( D \) is the access distance (radial, circumferential, or both) travelled from the origin to the destination;
- \( D_o \) is the distance (radial, circumferential, or both) between the transit line and the origin;
- \( D_d \) is the radial (radial, circumferential, or both) distance between the transit line and the destination;
- \( D_R \) is the ride (radial, circumferential, or both) distance travelled;
- \( R \) is radius of the ring line;
- \( y_R \) is ride cost per unit distance per passenger;
- \( H_{RL} \) is headway on the radial line;
- \( H_{RN} \) is headway on the ring line;
- \( y_T \) is transfer penalty that passengers suffer in case they need to transfer from one rail line to another;
- \( y_w \) is the wait cost per hour per passenger;
- \( y_T \) is the transfer cost per transfer per passenger;
- \( \zeta_{RL} \) is 0, 1, 2, 3, or 4 in case a transfer is needed on radial lines; and
- \( \zeta_{RN} \) is 0, 1, 2, or 3 in case a transfer is needed on ring lines.

We employed a fixed generalized access cost per unit distance for this analysis, which is used to calculate both access cost and egress cost functions:

\[ y_a(r, \theta) = y_a \]  
(8)

For the input data of this model, we required a transit OD matrix that showed the demand for travel between each zone pair. We also required coordinates of each zone’s centroid. With this input data, minimum passenger cost matrices for the current and extended network were obtained. Table 1 shows the unit cost factors used for the model.
Table 1. Unit cost values for Shanghai.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value of wait cost $\gamma_w$</td>
<td>20 CNY/hr./passenger*</td>
</tr>
<tr>
<td>Capital cost $\gamma_L$</td>
<td>59.3 thousand CNY/km/day*</td>
</tr>
<tr>
<td>Operating cost $\gamma_o$</td>
<td>32.8 thousand CNY/km/day*</td>
</tr>
<tr>
<td>Passenger access cost $\gamma_a$</td>
<td>2.8 CNY/km/passenger*</td>
</tr>
<tr>
<td>Passenger ride cost $\gamma_r$</td>
<td>0.56 CNY/km/passenger*</td>
</tr>
<tr>
<td>Transfer disutility $\gamma_t$</td>
<td>2.17 CNY/transfer/passenger*</td>
</tr>
<tr>
<td>Wait time factor $k$</td>
<td>0.5</td>
</tr>
</tbody>
</table>

* 1 CNY is equivalent to ~0.15 USD

RESULTS AND DISCUSSION

Figure 2 shows the cost-benefit analysis and the optimal alignment of ring lines in Shanghai for three different scenarios. The horizontal axis is the distance from the CBD, and the vertical axis represents the total cost value of a ring line (operating and capital cost minus total passenger benefit, as per Equation 1). The section of the graph with a negative vertical axis shows the radius of a ring line for the alternative where the benefit exceeds the cost of construction. For Scenario 1, we assumed the current network without a ring line and applied the ring line model to compare the optimum location of a single ring line with the alignment of the current ring line. This scenario only allows one ring line in the network. We found that $R=7$ km, centered at the CBD, shows the minimum cost-benefit value. The optimum radius of the ring line was found to be 1.7 km larger than the current Shanghai ring line (Line 4), which has an average radius of 5.3 km. Although the specific process of planning and selecting the current ring line in Shanghai has not been published to date, it is known that the line is partially located on a previously constructed track and the existing road network. However, the difference between the optimal ring radius and the current radius can still be examined. The discrepancy could be attributed to the existence of latent transit demand; Shanghai has experienced a recent unprecedented economic and population boom and, thus, the network and transit demand in 2004, when the first ring line was constructed, was very different from the current population and job distribution. Also, envisioning a possible second ring line can potentially impact the optimal alignment of the inner ring line, and shift it closer to the CBD, as in Scenario 3.

Scenario 2 is a cost-benefit analysis for the second ring line considering the existing ring line. The result provides a range of 10 to 11 km from the CBD as the global minimum cost-benefit value for the alignment. The construction of the proposed second ring line will make the current ring line (Line 4) the inner ring and the proposed second ring line an outer ring. We can also observe another local optimal value of 16 km from the CBD. The results of this model were communicated to Shanghai City Comprehensive Transportation Planning, which is the governmental body responsible for planning the future Shanghai metro network. They expect the
average radius of the second ring line in Shanghai to have a similar range of 10 to 12 km, although the plans are not yet finalized (20).

Scenario 3 tests the impact of the presence of a first ring line of radius 11 km (similar to the optimal alignment of the second line in Scenario 2) on the optimal alignment of a second ring line. The ring-radial model should be able to suggest either an inner or another outer optimal ring as the case may be. The results revealed a radius of 6 km from the CBD as the optimum location of the second ring line, a much closer location to the radius of the current ring line (Line 4) in Shanghai.

Comparing Scenario 1 and 3, it is observed that the optimal inner ring shifts closer to the CBD when an outer ring exists in the network. This finding suggests that plans for a second ring line can impact the optimal location of an inner ring line. The alignment of the original first ring line cannot be changed, but it is important to understand whether the future location of a second ring line will negatively impact the ongoing operation of the first ring. Thus, this scenario helps to test whether the first ring line is still located at, or close to the best possible alignment.

![Figure 2](image1.png)

Figure 2. Total cost (Capital and operating cost minus total passenger benefit) of the ring line for different scenarios based on the distance from the city centre.

Figure 3 shows the recommended second ring line range of 10 to 11 km on the Shanghai metro network.
As we did not have zonal population data for the analysis, we obtained the locations of cell phone users on a typical workday in Shanghai as an indicator of population and employment concentration. As shown in Figure 4(a), the suggested second ring line range mainly covers high-density (darker shadow) areas, except for the southeast section. The optimum range of the second ring line is shown to pass through high-density areas, supporting the third characteristic of ring lines introduced by Vuchic (11).

We analyzed zones that would obtain the greatest total benefit from introducing the second ring line. Considering the OD flow in the analysis, we represent the nodes with the greatest benefits by black dots in Figure 4(b). The benefits were calculated based on the demand for each station and total passenger cost saving by introducing the second ring line. The results demonstrate that the stations beyond the outer ring stand to gain the greatest benefit in terms of total passenger cost savings. This observation is highly dependent on the OD patterns, and anticipated changes to the route choices of passengers will be altered following the introduction of the second ring line in Shanghai. This observation is consistent with the expectation of an outer ring line, which will primarily benefit trip-end passengers located close to the ring line or passengers on an outer section of a radial line who transfer to another radial line in the outer section. By introducing an outer ring line, these passengers bypass the additional ride time toward the CBD to make their transfer.
In addition, we performed a sensitivity analysis to identify the changes in total cost values and optimal alignment of the ring line for Scenario 2, as shown in Figure 5. Figure 5(a) presents the changes in the value of time and the result on the total cost plot. The increase in the value of time will result in changing the global optimum to a previously local optimum radius of 16 km. By decreasing the value of time, the ring line will not be very desirable, and the cost of operation and construction will exceed the total benefit of having the ring line.

All reported data and analysis are based on existing metro OD observations. As such, we cannot consider any induced demand from other transportation modes or zones not well served by the current rail transit network. A new rail line, especially in areas not served well by high speed transit can induce new demand. However, the current model shows that, with the same OD
distribution, there are still situations where a new ring line would be beneficial. The induced demand can make the ring line even more desirable.

Consequently, we have tested different OD demand factors for the sensitivity analysis, while keeping trip distribution constant. Although this sensitivity analysis will not explicitly address induced demand, analyzing the sensitivity of the optimal ring line with respect to a total demand factor is still worthwhile. We tested 150%, 125%, and 110% increases in total demand with the same OD distribution and the decrease in total demand to 80% of the baseline. Similar to previous cases, an increase in total demand makes the second ring line more attractive, as shown in Figure 6(b). In addition, a 150% increase in total demand also changes the global minimum radius of the second ring line to a 16 km radius, similar to the case of a decrease in ride cost. Assuming a similar growth rate of the total metro OD demand to the population growth rate, 1.67% per year, of Shanghai in 2014 (36), we expect the total metro demand to reach 125% by 2027, and 150% by 2038. Therefore, conducting this sensitivity analysis will prove essential in determining the potential benefit of the new ring line considering future demand and its potential effect on the optimum transit network.

![Figure 5](image_url)

Figure 5. Sensitivity analysis of the changes in the total cost of a second ring line for changes in (a) Value of Time and (b) Demand.
SUMMARY AND CONCLUSIONS

In this study, we analyzed the Shanghai ring line using the long-term planning model for ring-radial urban rail transit networks developed by Saidi, Wirasinghe, and Kattan (16). The model was extended to optimize a possible second ring line for the purpose of long-term planning in Shanghai. A total of three scenarios were tested. In the first scenario, we used the Shanghai network assuming no ring line, and optimizing one ring line in the network. We found that the optimal radius of the ring line is slightly larger than the average radius of the existing Shanghai ring line (Line 4). In the second scenario, we used the Shanghai network with the current ring line to optimize a second ring line. The optimal location of the second ring line was found to be at a distance of 10 to 11 km from the CBD. In the third scenario, we tested a hypothetical case of one ring line at a radius of 11 km instead of the current ring line, and we used a ring-radial rail transit model to optimize a second ring line. This scenario showed that the second ring line is feasible and optimal at a radius of 6 km from the CBD, a radius very close to the current 5.3 km ring line. Taken together, the results for the three scenarios demonstrate that the location of one ring line will impact the optimal location of the second ring line. Therefore, if an outer ring line is planned for construction, the optimal alignment of the inner ring line may change. The alignment of the original inner ring line cannot be changed after construction and, thus, it is important to ensure that while a second ring line may be planned later, the original ring line is located at the best possible alignment and will not be negatively impacted by the second ring line. This problem can be handled in two ways. First, it is important to consider the possibility of a second ring line in the original long term transit network plan. Or, if such long term planning has not occurred, the objective should be to optimize the alignment of the new line and to maintain the effective operation of the inner ring line.

We conducted a sensitivity analysis and found that an increase in value of time and an increase in demand will create a more desirable ring line, while shifting the optimal radius of the ring line further away from the CBD. Additionally, by analyzing all of the attraction and production nodes, we found that by introducing an outer ring line, nodes located outside of this ring will obtain the greatest benefit in terms of total passenger cost savings.

The results from this study are particularly useful for cities considering an expansion of their transit network. Unlike simulations and agent-based models, this long-range model for the planning of ring transit lines is easily transferable to other transit networks. Therefore, given access to current and future OD data and transit network data, the model can be directly implemented for any given city.

However, one of the main limitations of this study is the use of the metro station OD data as the input for the model. One of the primary purposes of a ring line (or any metro line in general) is to effectively service new catchment areas not served well with the current radial transit system. The use of transportation or land use zonal OD data can address this issue, model the passenger route choices, and provide detailed trip-end movements and thus result in a more accurate cost-benefit analysis for different locations of the ring line. Since we only had station OD data (not transportation zone OD data) for the Shanghai case study, trip attraction and production nodes remain the same with without a ring line. Thus, the new ring line is only optimized to create faster routes for the same passengers with the same station origin or
destination. This limitation could have been resolved by using transportation zone OD as the input.

ACKNOWLEDGMENT

This work was funded in part by the Natural Sciences and Engineering Research Council of Canada (NSERC), the Killam Trusts, Calgary Transit, the Urban Alliance, the University of Calgary, and the Schulich School of Engineering. This paper is based on a joint case study between the University of Calgary, Canada and Tongji University, China. The authors would like to thank Bizhuang Chen, Zhiguo Dong, and Yunzhang Shen from the Shanghai City Comprehensive Transportation Planning Institute for their valuable time and input. We greatly appreciate the Shanghai Traffic Information Center for providing the Shanghai cell phone concentration data. We would also like to thank Yin Wang and Zheng Meng from the Department of Transportation Planning in Beijing for providing valuable insight into the Beijing metro ring lines. Finally, we thank Shichao Sun for providing data on the Shanghai metro.

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