Vulnerability Analysis of Bus Network Based on Land-Use Type of Bus Stops: The Case of Xi’an, China

Yanan Zhang ¹, Hongke Xu ¹, Qing-Chang Lu ¹, Shan Lin ¹,* and Jiacheng Song ²

¹ School of Electronic and Control Engineering, Chang’an University, Xi’an 710064, China; yananzhang@chd.edu.cn (Y.Z.); xuhongke@chd.edu.cn (H.X.); qclu@chd.edu.cn (Q.-C.L.)
² College of Mechanical and Electronic Engineering, Northwest A&F University, Xianyang 712100, China; jiacheng.song@nwafu.edu.cn
*
Correspondence: linshan@chd.edu.cn

Abstract: The urban public transport network is closely related to urban construction and is susceptible to external influences, especially the bus network (BN). The measurement of the changes in the performance of BN under disruptions plays an important role in the development of bus systems. This paper takes the land-use type around each bus stop to modify the standard coverage range and then combines the attractive service area of the stop and the passenger flow as the opportunity coefficient to propose an improved accessibility model. Finally, the vulnerability of the BN based on the improved accessibility model in different time periods under four disruptions is analyzed. Taking BN in the central area of Xi’an as a case study, the results show that the BN is less vulnerable when stops are associated with high land-use type attractiveness, and regions with a single land-use type have high vulnerability levels. In addition, the land-use disruption causes larger-scale network vulnerability than topological disruptions. An interesting result, opposed to common sense, is found in stops within the top 10% of topological disruption failure probabilities, i.e., the BN is the most vulnerable during the off-peak night period. This study supplements the coordinated development of public transport and land use in future planning.

Keywords: vulnerability analysis; bus network; bus stop coverage; land-use type; accessibility model

1. Introduction

Urban public transport typically has a large scale in terms of city infrastructure and the number of passengers, especially the bus system, which is one of the most important transit systems in urban areas. In most cases, buses have a shared right-of-way with other vehicle traffic, which makes their operation sensitive to random disruptions arising from fluctuations in vehicle flows and traffic jams. Bus stops are important connecting parts in the bus network (BN), and if the stops are disrupted, serious negative consequences for passengers are caused. For example, passengers might be unable to arrive at their destination on time, or at all, and the passengers waiting for a bus can expect delays or even canceled runs. Therefore, it is necessary to analyze the performance of the BN when bus stops are attacked.

The effects of network disruptions and accidents can be quantified in terms of the vulnerability of the network [1]. In previous studies, the measurement and evaluation methods of vulnerability have been classified as connectivity vulnerability, accessibility vulnerability, and capacity vulnerability [2]. Moreover, vulnerability analysis based on the accessibility index is a useful approach [3]. Accessibility, in broad terms, is a measure of the potential of opportunities [4] and can impact and measure a bus network’s performance and service. Accessibility in this paper is based on the discussion of the attractiveness of opportunities [5].

To provide better and more extensive bus services, it is not only necessary to set up more bus routes or increase the frequency of departure, but the degree to which passengers...
access the bus service should also be considered. Access comprises the opportunity to use the public transport system based on the proximity to the service and its cost. Buses are unlikely to be used as a mode of travel if the cost or distance to access their services at a certain place is too large [6]. Bus stops are the method by which passengers use this mode of travel. Therefore, the distance within which the bus stop can attract passengers will affect the likelihood of a person choosing the bus as a travel mode. In this paper, bus stop coverage is used to measure the opportunities for passengers to access bus stops. Bus stop coverage refers to a circular area range and takes the specified value given by the standard specification as the radius. However, the land-use type of an area can be used to describe its attractiveness in terms of the opportunities it offers for transit passengers [5], and the influence of different land-use types on the access distance of passengers choosing bus travel is different. Based on the above discussion, the land-use types around the bus stops can have some specific attractive characteristics for passengers. Therefore, the coverage area of the bus stop should be modified according to the type of land used in order to attract passengers.

Being that bus stops are the important connecting parts in a BN, once the stops are attacked, it will affect the operation of the bus system. In addition, the vulnerability of the BN when stops are attacked can be measured by the accessibility model. Therefore, this paper aims to consider the research gap in the influence of land-use types around the bus stops as an attractiveness index to reflect the effective area of bus stops based on the accessibility model and analyses of the vulnerability results, according to which the bus stops are attacked under four types of disruptions. The main motivation of this paper is to build on the relationship between accessibility and land-use types around stops, specifically in the context of BN, to gain new insights into vulnerability measures.

The remainder of this paper is organized as follows. In Section 2, the literature on vulnerability based on the accessibility model and land-use type is reviewed. In Section 3, the traditional accessibility model and the modified accessibility model considering land-use types around bus stops for the measurement of network vulnerability are presented. The case study area and data process are described in Section 4. Then, the results of the vulnerability of a BN under four kinds of disruptions at four time periods are shown in Section 5 and discussed in Section 6. Finally, the conclusions are summarized in Section 7.

2. Literature Review

Research on vulnerability first started in the 1970s in the field of disaster research and quickly spread to other research fields, such as transportation studies. Transport system vulnerability was first defined in terms of sensitivity indices to hazards that can result in considerable reductions in road network serviceability and accessibility [1]. Although the exact definition of transport system vulnerability changes between different studies, in general, these studies cover two key aspects of network vulnerability: the evaluation for the reduction in transportation network performance under attacks [7,8] and the identification of the important components of the transportation network [9]. Similarly, in this study vulnerability is defined as the changes in the network due to disruptive events.

Due to the exposed nature of bus operating conditions, a BN can be affected by common disturbances such as adverse weather and traffic congestion. Since bus networks are an important part of urban infrastructure, disruptions can result in serious consequences, especially for passengers. Depending on the effect of the disturbance type they model, transportation network vulnerability studies can be categorized into connectivity vulnerability [10], capacity vulnerability [11,12], and accessibility vulnerability [13–15]. Although the analysis of disturbances in connectivity or capacity is important for planning and emergency response operations, accessibility vulnerability can intuitively reflect the perspective of the passengers.

Several alternative definitions of accessibility have been proposed in the literature, and there are some differences between these. The concept of accessibility has been discussed in a wide range of contexts and has many different definitions. Ingram introduced
two notions of accessibility, which are used in public transport accessibility analysis [16]. Moreover, a model to measure public transport accessibility has been proposed from accessibility figures and sub-accessibility figures [17,18]. Based on existing research, this paper aims to improve BN accessibility by describing the degree of connection between two specific bus stops, which may be assessed in the function of opportunity attraction and impedance; this allowed for discernment of the accessibility of a given stop by taking into account all destinations within a certain region. Accessibility is a fundamental concept in transportation analysis and urban planning and is frequently linked to the concept of vulnerability [3]. Accessibility vulnerability analysis can integrate a series of static and dynamic factors to reflect the consequences of networks under disruptions, as has been conducted in previous studies [2]. To measure the performance of a transport network before and after disruptions, accessibility changes are used to estimate the quantification of vulnerability. Accessibility-based vulnerability methods have been used in a variety of different contexts, of which we now provide some examples: an accessibility-based methodology addressing travel modes was developed to evaluate transportation network vulnerability under flooding impacts [19] to estimate the consequences of landslide hazard in some regions, and the road network vulnerability was measured by the decrease in accessibility [20]. To identify the direct impact of extreme floods on road networks, this study modified accessibility measures to include population and average shortest travel time in the analysis method [21]. Additionally, the performance of a transport system after flooding was evaluated based on vulnerability changes related to accessibility to grocery shops [22]. Accessibility methods have also been integrated into multi-criteria vulnerability assessment methods, for example, the measurement of transport networks based on accessibility could identify the critical links under natural disasters [10] and link closure disruption [23]. Moreover, critical locations can also be identified in vulnerability analysis and may be measured by different factors impacting accessibility, such as the changes in the volume under different network states [24–26]. The vulnerable regions can also be recognized by using accessibility vulnerability analysis, e.g., the local vulnerability of some traffic regions can be captured under flood scenarios [21]. This shows that the accessibility-based method can analyze vulnerability from multiple perspectives. In this research, accessibility is used to analyze BN vulnerability. Different indexes were considered compared with accessibility models in previous studies. Traffic factors, such as travel demand, were considered in accessibility analysis, which can reflect the appropriate resource allocation strategies [27]. Travel cost and travel time were also used as a basis for accessibility changes [28] and could reflect the contribution of traffic factors to the accuracy of accessibility-based vulnerability assessment. Passenger flows can more directly reflect the degree of accessibility in a transportation system [29–31]. Socio-economic conditions can also impact the transportation network [24]. The Hansen accessibility model was proposed to determine the accessibility patterns within metropolitan areas; it is a model that can combine reachable opportunities and travel impedances of a place [4]. In some Hansen accessibility-based models, travel cost [32,33], travel time [21,34], and average distance [16,35] are used as impedance functions. This paper improved the Hansen accessibility model via the consideration of additional factors. Land use, as one of the elements of urban functions and development changes, can be considered in accessibility measurement [30]. The impact of land use on transportation in the development of cities has been well analyzed [36,37]. Land-use characteristics around stations can influence opportunities, and land-use variables are measured in terms of the independence degree in the accessibility approach to measure a network’s vulnerability [34]. Land use is considered in a bilevel programming model to analyze the relationship between transport and land cover types [38]. A land use/transport interaction model is presented to provide rich insights for urban growth [39]. Bus stops located in different land use environments have an impact on the phenomenon of bus bunching, which affects the reliability of bus network [40]. To improve transport land-use planning integration in practice, accessibility indicators are used to generate and select effective
combinations of transport and land-use interventions [41]. To investigate the relationship between land-use/land-cover types and transport characteristics, traffic zones generated by partitioning parcels with single land-use/land-cover types are quantified by driving accessibility, cycling accessibility, and walking accessibility [42]. Hence, understanding the relationships between land use, accessibility, and vulnerability in transport networks is important for developing functional urban areas.

From the above discussion, we can conclude that the vulnerability of a BN can be analyzed according to the accessibility indicators. The relationship between accessibility and land-use types of transportation has been well studied; however, there is still limited research that integrates land use and vulnerability and analyzes accessibility and land-use types around bus stops. In this paper, we address the question of how the land-use types around the bus stops affect the vulnerability of a BN when bus stops are disrupted, and we also study how these elements change during different periods throughout the day.

3. Methodology

3.1. Traditional Accessibility Measure for BN Vulnerability

When analyzing the accessibility of specific points, such as the original stop to the destination stop, a function of some hindering factors hampering the original bus stop from accessing the destination bus stop via transportation and the opportunities at the destination bus stop can be used to calculate accessibility. The Hansen traditional accessibility index in its normalized form is shown in Equation (1):

$$A_i = \frac{\sum_{j=1}^{n} B_j I_{ij}}{\sum_{j=1}^{n} B_j}$$

(1)

where $A_i$ is the accessibility of the original bus stop $i$; $B_j$ is the opportunities coefficient of destination stop $j$; $n$ is the number of stops; and $I_{ij}$ is the impedance that influences accessibility from $i$ to $j$.

In the literature, some impedance functions are used in accessibility models, such as travel cost, distance, and travel time. In this study, the travel time between two points is used as the impedance function and the passenger flow is used as the attractiveness metric for the destination stop. Moreover, when there are multiple specific points in an area, the accessibility of the network should consider all destination stops. Thus, the traditional accessibility of BN can be calculated via Equation (2):

$$A_{Tc} = \frac{\sum_{j=1}^{n} \sum_{j\neq i}^{n} F_j T_{ij}}{\sum_{j=1}^{n} F_j}$$

$$T_{ij} = \frac{1}{t_{ij}}$$

(2)

(3)

where $A_{Tc}$ is the traditional accessibility of all bus stop in area $c$, and $(1, \ldots, j, \ldots, n \in c)$; $T_{ij}$ is the travel time impedance coefficient from origin stop $i$ to destination stop $j$; $t_{ij}$ is the actual travel time from origin stop $i$ to destination stop $j$; and $F_j$ is the passenger flow arriving at the destination stop $j$.

The definition of vulnerability is the change in accessibility under each disruption. According to the accessibility model mentioned above, the vulnerability of BN under disruptions can be calculated from Equation (4):

$$V_{Tc} = \frac{A_{Tc} - A_{aTc}^{a}}{A_{Tc}}$$

(4)

where $A_{aTc}^{a}$ is the traditional overall accessibility of BN in area $c$ after the disruption $a$; and $V_{Tc}$ is the vulnerability of BN of stop $i$ in area $c$ for the disruption $a$ by calculating in traditional accessibility.
3.2. A Modified Accessibility Model Considering Land-Use Type

Based on the above shown analysis of the vulnerability of BN measured by using the traditional accessibility model, a modified Hansen accessibility metric for vulnerability analysis is proposed. Unlike the traditional Hansen metric, this model aims to account for the effect of land use around the bus stop on the attractiveness of the stop to passengers. In previous studies of the measurement of accessibility, opportunities only used passenger flow to reflect. Incorporating land-use characteristics into the metric can also help to capture some of the latent opportunities. The parameters of the Hansen model are modified in this paper, and the passenger flow and land-use type are introduced. Land-use characteristics around bus stops can influence the opportunities, and we focus on considering different land-use types to modify the coverage area of bus stops and obtain a new bus stop attractive service area. Moreover, the passenger flow is introduced to express the opportunity coefficient in the modified accessibility model, and the land-use type factor is taken to modify the passenger flow. The results of attracting passengers to choose bus travel via bus stops with different land-use types are different.

Moreover, bus stop coverage is used to measure the opportunities for passengers to access bus stops in this paper, and the land-use types around the bus stops can confer specific attractive characteristics. Therefore, the coverage area to attract passengers to the bus stop should be modified according to the type of land use. Taking the accessibility of each stop in standard coverage as a unit and combining the modified coverage area to obtain the modified accessibility model, the modified accessibility of a BN considering land-use type can be calculated via Equation (5).

\[
A_{Mc} = \sum_{i=1}^{n} \frac{\sum_{j=1}^{n} F_j L_j T_{ij}}{S}
\]

where \(A_{Mc}\) is the modified accessibility of all bus stops, considering the land-use type to modify the opportunity coefficient; \(C_i\) is the attractive service area of bus stop \(i\) considering land-use type; and \(L_j\) is the land-use type attractiveness index at stop \(j\). The land-use type attractiveness index is used to express the modified factor, which is based on the definition of land-use mixture degree metric [43] (see Equations (6) and (7)).

\[
L_j = -\sum_{k=1}^{K} \phi_{jk} \ln(\phi_{jk}) + 1
\]

\[
\phi_{jk} = \frac{u_{jk}}{S}
\]

where \(\phi_{jk}\) is the importance of land-use type \(k\), and it is the ratio of type \(k\) around the bus stop \(j\); \(K\) is the total number of land-use types in this area; \(S\) is the standard bus stop coverage range, and it is a fixed value and restricted in different cities or regions; and \(u_{jk}\) is the area of type \(k\) within the standard bus stop coverage range \(S\) at stop \(j\).

The accessibility of a BN expresses the performance of the entire network. In addition, bus stops under different land-use types have different degrees of attractiveness. The bus stop’s attractive coverage area of land-use type \(k\) is introduced to reflect the attractive service ability for each type at one stop, which is a circular area with the bus stop at its center. The attractiveness radii based on existing research are shown in Table 1 [44].

Based on the above discussion, the modified standard bus stop coverage considering land-use type is an attractive service area, and it is expressed in Equation (8). The attractive coverage area of each land-use type is expressed in Equation (9).

\[
C_i = \sum_{k=1}^{m} S_{ik}
\]

\[
S_k = \pi \cdot r_k^2
\]
where $S_k$ is the attractive coverage area of land-use type $k$, and it can be calculated from Table 1; $r_k$ is the attractive radius of land-use type $k$; and $S_{ik}$ is the total area of land-use type $k$ within the $S_k$ at stop $i$.

Table 1. Attractive radii of bus stops for different land-use types.

<table>
<thead>
<tr>
<th>Type ID (k)</th>
<th>Land-Use Types</th>
<th>Attractive Radius/m ($r_k$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Residential</td>
<td>450</td>
</tr>
<tr>
<td>2</td>
<td>Commercial</td>
<td>300</td>
</tr>
<tr>
<td>3</td>
<td>Education</td>
<td>200</td>
</tr>
<tr>
<td>4</td>
<td>Office</td>
<td>450</td>
</tr>
<tr>
<td>5</td>
<td>Hospital</td>
<td>200</td>
</tr>
<tr>
<td>6</td>
<td>Public</td>
<td>560</td>
</tr>
<tr>
<td>7</td>
<td>Industrial</td>
<td>560</td>
</tr>
</tbody>
</table>

Taking the land-use type around stop $i$ as an example (Figure 1), within the attractive coverage area of type 1, $S_{i1}$ is the yellow part (the area belongs to type 1) within the black circle (Figure 1a). In the attractive coverage area of land-use type 2, $S_{i2}$ is the blue part (the area of type 2) within the black circle (Figure 1b). Other types of area $S_{ik}$ analysis methods are as above. Based on this analysis, the attractive service area under the considered land-use type for each stop is obtained.

![Figure 1](https://example.com/figure1.png)

**Figure 1.** Area of land-use types within the attractive coverage areas of stop $i$.

### 3.3. BN Vulnerability Model Considering Land-Use Type

In this paper, according to the disruptions of different characteristics of each stop, the subjective stops fail in the bus network, and this failure means subjective stops remove from the bus network. Four types of disruptions are simulated in the vulnerability analysis of the BN, and the disruptions are (1) the number of routes a stop served (stops with a higher degree or number of routes served have a higher chance to fail); (2) stop degree centrality (stops with higher degree centralities have higher failure probability); (3) land-use mixture (failure probability increases with higher mixture of land-use types); and (4) random failure (control case where all stops are equally likely to fail). Disruptions 1 and 2 are referred to...
as topological disruptions, disruption 3 as a functional disruption, and disruption 4 as a control experience.

In addition, this paper uses the normal situation (no stop failure) to analyze the network performance when one or more stops fail. Therefore, the decisions of passengers when the stops fail are not considered. According to the analysis of disruptions, the failed stops can be obtained from the probability of disruption. Moreover, disruption 4 uses random probability. The failure probability of stop \( i \) under different disruptions is shown in Equation (10).

\[
prob_{ai} = \frac{c_{ai}}{\sum_{i=1}^{n} c_{ai}}
\]

where \( prob_{ai} \) is the probability of stop \( i \) under disruption \( a \) and \( c_{ai} \) is the characteristic value under disruption \( a, a = 1, 2, 3 \). In detail, \( c_{ai} \) is the number of routes served in stop \( i \), \( c_{ai} \) is the number of stops that link with stop \( i \), and \( c_{ai} \) is the value of the land-use type mixture of stop \( i \). In this paper, bus stop failure refers to the removal of this stop while retaining the edges.

The modified BN vulnerability model is based on the modified accessibility model, which analyzes the vulnerability of BN by simulating four types of disruptions. Therefore, the BN vulnerability model considering land-use type can be shown as Equation (11):

\[
V_{Mc} = \frac{A_{Mc} - A_{Mc}^{a}}{A_{Mc}}
\]

where \( V_{Mc} \) is the vulnerability of the BN in area \( c \) under the disruption \( a \) by calculating in the modified accessibility model; \( A_{Mc} \) is the accessibility of the BN in area \( c \) under normal operation; and \( A_{Mc}^{a} \) is the accessibility of the BN in area \( c \) under disruption \( a \).

4. Study Area

Xi’an City is located in the central part of Guanzhong Plain in China, covering a surface area of 1066 square kilometers. Xi’an City’s central area (Figure 2a) is about 12 square kilometers, and is the core area of culture, tourism, entertainment, and commerce. It is found that almost all the main roads have bus routes in the case area, and the density of bus stops is different (the route distribution is shown in Figure 2b).

In terms of land-use types, we divide the city central area of Xi’an into the following land-use types: resident traffic type (RTT), commerce traffic type (CTT), education traffic type (ETT), office traffic type (OT), hospital traffic type (HTT), public traffic type (PTT), and industry traffic type (ITT). The land type division of the study area is based on the road...
network mode in the Amap, and the land-use type distribution is indicated by a different color and is shown in Figure 3.

![Figure 3. Land-use type distribution of the case study area.](image)

The commercial traffic zone accounts for the largest proportion, followed by the residential traffic zone. It shows that commercial and residential traffic zones occupy an important position in this case area. The proportion of each type is shown in Table 2. To associate land use and bus stops, the standard bus stop coverage range according to local traffic requirements is used, and this range covers a circular area with a radius of 300 m in Xi’an City. ArcMap is used to divide the range of each stop and calculate the proportion of each land-use type within the standard bus stop coverage range.

Table 2. The proportion of land-use types.

<table>
<thead>
<tr>
<th>Land-Use Types</th>
<th>Proportion/%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td>28</td>
</tr>
<tr>
<td>Commercial</td>
<td>40</td>
</tr>
<tr>
<td>Education</td>
<td>10</td>
</tr>
<tr>
<td>Office</td>
<td>10</td>
</tr>
<tr>
<td>Hospital</td>
<td>4</td>
</tr>
<tr>
<td>Public</td>
<td>8</td>
</tr>
<tr>
<td>Industrial</td>
<td>0.01</td>
</tr>
</tbody>
</table>

In addition, there are 110 bus routes and 1124 OD pairs between stops in this area. The data used for analysis include the passenger flow of the 51 stations in the central area from Xi’an Transportation Bureau and the real-time travel time between the OD pairs from Amap. To analyze the changes in the network performance more clearly, the passenger flow and travel time are divided into the following four time periods of five weekdays for separate analysis: morning peak hours (7:00 a.m.–9:00 a.m.), day off-peak hours (12:00 a.m.–2:00 p.m.), evening peak hours (5:00 p.m.–7:00 p.m.), and night off-peak hours (8:00 p.m.–10:00 p.m.).

In a real network, the situations in which stops with high failure probability failing at the same time in BN and only one stop failing in BN are very uncommon. Therefore, in this case study, we assumed 10% of the stops to randomly fail according to the disruption failure probability in each cumulative disruption experience and repeated this 200 times to obtain the mean value of failure probability.
5. Results

After model analyses and case experiments in previous sections, the accessibility and vulnerability of all stops of each period in the day are calculated. We normalize the accessibility values of each stop in the same period to discern the accessibility level of each stop in the network at the same period. This can better obtain the results and changes of BN vulnerability when some stops fail at a certain time. The normalized values are all in the range of 0 to 1 and higher values represent better accessibility. The values are shown in Table 3.

Table 3. Accessibility values of each stop at different period.

<table>
<thead>
<tr>
<th>Stop ID</th>
<th>Morning Peak</th>
<th>Day Off-Peak</th>
<th>Evening Peak</th>
<th>Night Off-Peak</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.13806</td>
<td>0.14253</td>
<td>0.13922</td>
<td>0.0149</td>
</tr>
<tr>
<td>2</td>
<td>0.13432</td>
<td>0.13739</td>
<td>0.14123</td>
<td>0.00492</td>
</tr>
<tr>
<td>3</td>
<td>0.44157</td>
<td>0.32909</td>
<td>0.50118</td>
<td>0.40749</td>
</tr>
<tr>
<td>4</td>
<td>0.16722</td>
<td>0.1503</td>
<td>0.194</td>
<td>0.06239</td>
</tr>
<tr>
<td>5</td>
<td>0.15011</td>
<td>0.15247</td>
<td>0.14735</td>
<td>0.07086</td>
</tr>
<tr>
<td>6</td>
<td>0.17138</td>
<td>0.16011</td>
<td>0.16173</td>
<td>0.08294</td>
</tr>
<tr>
<td>7</td>
<td>0.22007</td>
<td>0.18651</td>
<td>0.27011</td>
<td>0.24201</td>
</tr>
<tr>
<td>8</td>
<td>0.76236</td>
<td>0.76087</td>
<td>0.82402</td>
<td>0.81996</td>
</tr>
<tr>
<td>9</td>
<td>0.38587</td>
<td>0.40895</td>
<td>0.46025</td>
<td>0.58863</td>
</tr>
<tr>
<td>10</td>
<td>0.19008</td>
<td>0.18044</td>
<td>0.17914</td>
<td>0.16747</td>
</tr>
<tr>
<td></td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>51</td>
<td>0.65231</td>
<td>0.49884</td>
<td>0.70517</td>
<td>0.63674</td>
</tr>
</tbody>
</table>

To interpolate the calculated discrete accessibility data into a continuous function, the accessibility values within the study area are estimated using the values of the limited number of discrete points, i.e., the bus stops themselves. The radial basis function interpolation method from ArcGIS 10.2 is used: the RBF (radial basis function) interpolation method, which is a kind of neural network method. It can create a smooth surface with values that may lie outside the range of the sample data [45]. Users can select different RBFs and parameters that control smoothness according to their needs. This paper uses the latitude and longitude of a stop as a function of the x- and y-axes, and the reachability value of each stop as the z-axis. The accessibility of the BN in the four time periods is calculated and is shown in Figure 4.

It can be observed that the distribution of bus network accessibility is consistent in the first three time periods. Stops 20, 23, 25, 28, 34, and 35 exhibit higher network accessibility values. The variation within the network is relatively uniform during the day off-peak periods with concentrated values. However, during the night off-peak period, certain stops have higher network connectivity values across all four time periods, especially in the areas around Stops 20, 23, 25, and 28, which contradicts common knowledge. Due to the higher passenger flow and greater number of bus routes, averaging around 15, compared to other sites at any time of the day, the target site, which serves as a hub connecting surrounding sites, is more important in the transportation network. Any malfunction or disruption in these hotspot areas would greatly impact the network. Additionally, most bus routes cease operation during the night, resulting in some sites having no accessibility within the transportation network. Since this study normalizes the accessibility of all sites within the same period, the impact of the hotspots on the overall network accessibility is more pronounced during the night and higher than in other periods.

The target hot stops have higher traffic flow than other stops at any time of the day. In addition, there are more bus routes than other stops, and the average number of routes is about 15, which is much higher than the standard number. The target hot stops are the hub points connecting the surrounding stops in this area, which is important in a BN. If these hot stops fail, the network will be greatly affected. Moreover, most bus routes suspend their operations at night, which causes some stops to have no accessibility value. Since this study is to normalize the accessibility of all stops at the same time period in the BN, the
accessibility value of hot stops in the entire network is more obvious at night and higher than at other time periods. This makes the accessibility value more concentrated at some individual stops, and the gap is large.

![Contour map for the accessibility of the BN during different time periods.](image)

We now present results on the vulnerability measurements of the BN at different times of day under four disruption types. For each disruption type, the top and bottom 10% of stops are randomly assumed to fail according to the failure probabilities. The vulnerability value reflects how the BN’s accessibility changes when the stops fail under disruption at four time periods and the value is between 0 and 1. This means that higher values correspond to more significant negative impacts on the network. Each disruption event is randomly repeated 200 times to obtain the average and standard deviation of the vulnerability at four time periods and the results are shown in Figure 5.

As can be seen from Figure 5, the trend of vulnerability average under the four disruptions is roughly the same during different periods. Disruption 1, which is when the stops with higher degrees are attacked has the highest value, followed by disruption 2 (stop degree centrality), and disruption 3 (the stops with higher land-use mixtures), which have a slightly higher value than disruption 4 (random failure). Specifically, the network shows a lower vulnerability under disruption 3 than disruptions 1 and 2 because disruption 1 and 2 are directly relative to passenger service, and the traditional accessibility model focuses on the passenger flow and travel time. Therefore, when the BN is attacked by disruptions 1 and 2, the BN exhibits an obvious negative impact. However, when it is attacked by disruption 3, the network shows more stability in the measurement of traditional vulnerability. For the standard deviation, the vulnerability shows the most stable performance under disruption 1, but the largest fluctuation in BN vulnerability is under disruption 3 and reaches the highest vulnerability value during night off-peak hours in all cases. It is shown that the stops with the largest failure probability are vulnerable to attack under disruption 1, and once these critical stops are protected by the network, it effectively reduces network vulnerability and makes the network less susceptible to serious damage. However, the stop failure probability distribution is concentrated under disruption 3; once this type of disruption occurs, the network will be damaged on a large scale. This means that disruption 1 will
cause a higher level of network vulnerability, but disruption 3 will cause a larger range of network vulnerability.

![Figure 5](image.png)

**Figure 5.** The average and standard deviation of vulnerability.

In Figure 6, the effects of disruptions 1 and 2 are shown; these two disruptions are topology-based and showed the biggest vulnerability values during night off-peak hours. The operation of some bus routes is suspended at night, and certain routes with a large passenger flow throughout the day still operate at night; therefore, these routes account for a large proportion of passenger flow services. Moreover, the stops with a high failure probability under disruptions 1 and 2 are within these operating routes. Therefore, the stops with a higher failure probability under disruptions 1 and 2 have a higher proportion of vulnerability at night off-peak hours than at other periods. Additionally, due to the reduction in operating routes at night, fewer routes can be used for transferring, which makes the BN more fragile and vulnerable. In the case of topology interruption, the BN has the greatest vulnerability during non-peak hours at night, which is an interesting result.

![Figure 6](image.png)

**Figure 6.** The vulnerability of disruptions 1 and 2.
Setting the top 10% and bottom 10% of stops, in terms of failure probabilities from disruptions 1, 2, and 3, to fail, the vulnerability of the BN was calculated. It was found that the vulnerability of the top stops was higher than the bottom stops under disruption types 1 and 2 (shown in Figure 7a,b). Under disruptions 1 and 2, usually, a stop with a higher failure probability also has higher accessibility since these stops have high connectivity. Disruption 3 shows an opposing result, and the vulnerability of top stops is lower than the bottom ones (shown in Figure 7c). Under disruption 3, the failure probabilities of top stops represent the stops with high land-use mixtures, while the bottom stops represent more homogeneous land use around the stops. This shows that a high degree of land-use type mixtures can help the network resist the damage caused by disruptions, and a single land-use type will make the stop and network more vulnerable to disruptions. Therefore, a lower land-use type mixture confers higher vulnerability, meaning land-use type mixture and vulnerability are inversely related.

Another interesting finding is shown in Figure 8, i.e., according to the analysis of the land-use type attractiveness index \( L_i \) and the standard deviation of all land-use type areas \( CV_i \) of each stop, the \( L_i \) and \( CV_i \) are inversely proportional. Specifically, the top 10% stops of \( L_i \) have a high degree of mixing, and these were stops with the lowest standard deviation. The bottom 10% of stops have low mixing but the highest standard deviation. For a stop with a high degree of mixing, the distribution of each type is relatively uniform. On the contrary, the mixing degree of the stops is low, indicating that a certain land-use type is extremely prominent.

According to the abovementioned experiments, the vulnerability of the top 10% of stops is smaller than that of the bottom 10% under disruption 3. This proves that the factor of land-use type can effectively deal with network vulnerability. The changes in the traditional and modified vulnerability models under disruption 3 at four time periods are shown in Figure 9.

![Figure 7](image_url)
Figure 7. The vulnerability of top and bottom 10% stops under disruptions 1, 2, and 3. (a) Disruption 1; (b) disruption 2; (c) disruption 3.

By comparing these results, it is found that the trend of the vulnerability of the failure of top stop is higher during off-peak hours than during peak hours in both models. However, for the bottom stops, the trend of vulnerability is the highest during the morning peak hours. This may be because the residential area accounts for a large proportion of the attractive area of the bottom stops. Most people who live in residential areas need to travel to work or school during morning peak hours, and the passenger flow is therefore larger and more vulnerable than at other times. However, within the attractive area for top stops, there are many commercial, government, and public buildings, because these kinds of places are open during day off-peak hours, so most people need to come here to conduct business during day off-peak hours and therefore the area around top stops may be more vulnerable during day off-peak hours. It can be concluded that for stops with a single land-use type and a large difference in attraction degree, obvious high vulnerability results will be obtained. The analysis of land-use types proposed here will show more obvious results when applied to areas with more diverse land-use types than urban central areas.
Figure 8. The relationship of the land-use type attractiveness index and standard deviation.

Figure 9. Comparisons of traditional and modified vulnerability under disruption 3.

6. Discussion

Urban public transportation takes a large amount of demand and maintains the development of the urban green economy. They way by which more complete and reasonable development of the public transport system can be achieved has become an increasingly important issue, especially the bus system. Hence, this paper discusses the bus network vulnerability changes when bus stops are disrupted as a connecting part of the bus system, and this vulnerability measurement is based on the perspective of accessibility. The modified accessibility model considers the land-use type within the bus stop as the opportunity coefficient, which means that when the stop is located in different types of areas, the coverage is no longer a fixed value, and a reasonably attractive service area of bus stops can be obtained. This shows that accessibility analysis can be sensitive to the opportunities at each location, and it can measure different elements according to the focus of the model, emphasizing the need for different ranges of accessibility measures. Based on the disruption settings, the performance difference in the BN under topological disruptions and land-use disruption are analyzed. Moreover, all the experiments are simulated in four time periods in a day, and the influence of land-use type on BN at different time periods was obtained. Therefore, based on the results of this study, some policy recommendations can be provided. For
example, due to the gradual increase in passenger flow in the central urban area of the
city, the operation time of some bus routes can be extended. Second, the distribution of
passenger flow should no longer only be concentrated in specific locations, but rather it
should be more widely distributed. Therefore, some stops should increase the number of
night operation routes. Finally, the traffic demand of the region should be considered in
future urban planning, and the land-use type and public transportation should be closely
linked to benefit the urban economy and promote green sustainable development.

The bus network interacts with land use, which can lead to and promote the healthy
development of the city. However, since the central urban area is taken as a case study,
the number of land use types and the proportions of each type around each stop are very
similar, and this led to a relatively concentrated vulnerability result. Since the study area
is limited to a single city in China, some of the results may not be generalizable to other cities.
However, the vulnerability and accessibility models proposed in this paper can be used to
analyze the performance of bus networks with different characteristics in other areas.

In addition, the passenger is an important part of public transport; they participate
in different activities and have different time values, which will have different effects on
network vulnerability. Any decision they make when the bus network is attacked will have
a significant impact on the system. This means the network vulnerability is influenced
by how passengers evaluate the travel mode of the bus. The accessibility measured by
objective factors is imperfect because it cannot capture the passengers’ experience and
perception. However, perceived accessibility can be more comprehensive considering the
vulnerability of public transport accessibility [46,47].

Based on this study, future directions for research could focus on the following:
(1) other external factors that may affect the vulnerability of BN should be analyzed,
such as weather conditions, traffic congestion, policy, and the economy; (2) the vulnerabil-
ity of public transport should be depicted from the perspective of passengers’ experiences
and perceptions change; and (3) how the entire network performance changes when both
bus stops and edges fail should be investigated.

7. Conclusions

The rapid development of urban public transport requires more reliable and efficient
methods to be provided to planners. This research proposes an improved accessibility
measurement method based on taking the land-use type around each bus stop to modify the
standard coverage range and the land-use type as the opportunity coefficient in passenger
flow. The vulnerability of the BN under different types of disruptions at different time
periods is analyzed.

We find that the BN is the most vulnerable during night off-peak hours, which is highly
counter-intuitive. This is because for urban transportation, especially urban road transport,
the morning and evening peak hours are the times of the day that are the most important
for civilian transportation. During peak periods, there are large passenger and traffic flows;
therefore, the BN will have a large performance change if the disruptions occur. Second,
the results show that stops with higher topological failure probability are more vulnerable
at night off-peak hours than at other operating time periods, demonstrating that some bus
stops are more important at night than at other times. In addition, because of the reduction
in operating bus routes, the network is also more vulnerable. Third, for the four kinds of
disruptions, aiming at the top and bottom 10% targeted stops of the BN according to their
ranking, based on failure probabilities and setting a large number of random experiences
to analyze vulnerability, it is found that there are clear differences between topological
disruptions and functional disruption. On the one hand, the vulnerability of the top
stops is higher than the bottom stops in topological disruptions of target stops with high
connectivity. On the other hand, stops that are attacked based on land-use type mixtures
show the opposite result, i.e., the vulnerability of top stops is lower than bottom stops.
We find that higher land-use type mixtures correspond to lower vulnerability, meaning
land-use type mixture and vulnerability are inversely related. In addition, the attractive
area of land-use type at each stop is quite different, and obvious vulnerability results be obtained.

Vulnerability analysis of the BN is important for exhibiting the current BN conditions and providing a basis for decision making, infrastructure development, and comprehensive management. We used vulnerability analyses to better understand public transport and land use, and provide new and actionable ideas for researchers and managers in the urban development sector to develop strategies in the future.

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