RESEARCH ARTICLE

# Reliability of Coupled Subway and Bus Networks under Uncertainty

**Kaiye Gao**[1], **Rongquan Yu**[2], **Sicheng Zhang**[2] **and Di Wu**[3,*]

[1] School of Economics & Management, Beijing Forestry University, Beijing 100083, China
[2] School of Economics & Management, Beijing University of Technology, Beijing 100124, China
[3] School of Management Science and Engineering, Central University of Finance and Economics, Beijing 100081, China

## Abstract

**In urban public transport networks, subway and bus systems complement each other and together form a coupled system that serves passenger travel. However, a disturbance in either subsystem can propagate through coupling nodes across the entire network, thereby reducing overall operational efficiency. Most existing studies focus only on the reliability of a single mode, and few have analyzed the overall reliability of the system while considering the coupling relationship between the two. To address this gap, this paper proposes a probabilistic evaluation model to assess the reliability of the subway and bus coupling system. System reliability is defined as the probability that the network can meet all passenger demand given uncertain demand and limited road and rail capacity. The model accounts for passengers' travel behavior of "prioritizing the subway" and, by sequentially computing the load on each road section, the subway's share, and the remaining bus load, determines whether the system is reliable under a given demand combination. This provides an effective quantitative tool for the planning and optimization of integrated urban transportation systems.**

**Keywords**: reliability, coupled subway and bus system, demand uncertainty, capacity constraints, subway priority behavior.

## 1 Introduction

Urban public transportation is essential to the functioning of modern cities. It supports economic activity, enables everyday mobility, and promotes sustainable development [1, 16]. Among available modes, the subway and the bus are the two most widely used systems. Subways offer large capacity, high speed, and reliable travel times, while buses provide low cost, broad coverage, and flexible service that distributes flows, links regions, and serves the last mile [3, 4, 6, 9].

In practice these systems are coupled rather than independent [8, 12, 17, 21]. For example, during the morning peak many passengers prefer the subway for trunk travel while feeder buses deliver riders to stations. A delay on a key subway line can quickly crowd transfer stops, slow bus boarding, and spill congestion back to upstream routes. Conversely, a bus corridor bottleneck near a transfer hub can restrict access to stations, suppress subway boardings, and

**Submitted:** 27 October 2025
**Accepted:** 05 November 2025
**Published:** 29 January 2026

**Vol.** 2, **No.** 1, 2026.
10.62762/TSSR.2025.612115

***Corresponding author:**
Di Wu
blessudwu@gmail.com

**Citation**
Gao, K., Yu, R., Zhang, S., & Wu, D. (2026). Reliability of Coupled Subway and Bus Networks under Uncertainty. *ICCK Transactions on Systems Safety and Reliability*, 2(1), 3–10.

shift loads to parallel lines. Such interactions travel through coupling nodes and reshape demand and capacity across the network. A real-world example clearly illustrates these interactions. During the morning peak on May 30, 2024, a signaling fault on Beijing Subway Line 13 caused train delays and long queues at transfer hubs such as Lishuiqiao and Wangjing. Many passengers switched to parallel bus routes, which quickly became congested due to limited road capacity, further exacerbating the overall delays. This case highlights how disturbances in one subsystem can propagate through coupling nodes and degrade the performance of the entire multimodal network. Much prior research evaluates reliability mode by mode, implicitly assuming independence between subway and bus [5, 13, 22, 23]. See literature review part for a summary. This overlooks demand shifting at transfer nodes and the conversion between road and rail capacity. As a result, single mode metrics can misestimate network reliability, miss cascade effects from local disturbances, and lead to suboptimal planning decisions on capacity, scheduling, and redundancy.

To address this gap, we develop a probabilistic evaluation model for the coupled subway and bus system. We define system reliability as the probability that the network can serve all trips under uncertain demand and limited capacities on both road and rail. The model reflects subway first travel behavior, computes section loads sequentially, allocates the subway share, and assigns the remaining load to buses under coupling constraints. A numerical example illustrates the full workflow from demand generation to final reliability and examines the influence of key parameters. The results show when single mode assessments overstate or understate real performance and provide guidance for capacity allocation, stage based planning, and resilience improvement.

## 2 Literature Review

Research on subway reliability has focused on headway regularity, on time performance, timetable stability, redundancy, and the effects of signaling and disruptions on section operations. Typical indicators are derived from schedules and realized headways, and modeling approaches examine how design choices and control strategies stabilize operations and maintain capacity under perturbations [14, 17, 19].

Bus reliability studies are more passenger centered. They emphasize waiting time, schedule adherence, on time arrival, stop congestion, and perceived service variability. Recent work incorporates capacity constraints and demand uncertainty to capture the imbalance between supply and demand during peak periods. It also evaluates reliability under stochastic operations and limited road space [8, 16]. Recent work incorporates capacity constraints and demand uncertainty to capture peak period supply and demand imbalance and to evaluate reliability under stochastic operations and limited road space [8, 16, 18].

With the rising complexity of urban networks, scholars have begun to study multimodal reliability that includes subway, bus, and other modes such as taxi and shared mobility [11, 15]. Many contributions use network topology based frameworks to measure the effect of node failures or capacity reductions on overall efficiency [7, 12, 20, 24]. However, most models still treat subsystems as independent and do not fully represent dynamic passenger transfer and the conversion between road and rail capacity at coupling nodes [2, 16, 19]. Work specifically on the coupled subway and bus system is emerging, including analyses of network structure, vulnerability, and reliability under route choice or travel behavior assumptions. However, these studies are often static and do not jointly consider capacity limits, demand uncertainty, and behavioral preferences [10, 13, 17, 23, 24]. Against this background, our contribution is a tractable probabilistic model that explicitly couples subway first behavior with section level capacity constraints to evaluate the probability of meeting all trips. This framework quantifies cascade effects, identifies bottlenecks, and supports planning and optimization for integrated urban transportation under uncertainty.

The rest of this paper is organized as follows. Section 3 describes the system and model the reliability, Section 4 verifies the model through a numerical study, and Section 5 concludes and proposes future work.

## 3 System Description

We consider a coupled network with one subway line and one bus line, where a subset of stations is co-located and function as transfer nodes. Passengers are assumed to prioritize the subway because it operates on dedicated tracks with higher frequency, larger capacity, and lower travel time variability than buses. In many cities, buses are designed as feeders with integrated ticketing and coordinated transfers, making rail the fastest and most reliable choice for the main trip segment, especially during peak periods. For simplicity, we focus on interactions that occur at

**Table 1.** Combinations.

| *Case No.* | *(D1,3, D3,5, D5, 7, D7,9, D9,11)* | *Probability* | *G1* | *G2* | *G3* | *G4* | *G5* | *G6* | *G7* | *G8* | *G9* | *G10* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | (4,4,4,4,4) | $0.3^5$ | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| 2 | (4,4,4,4,6) | $0.3^4 \times 0.7$ | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 6 | 6 |
| 3 | (4,4,4,6,4) | $0.3^4 \times 0.7$ | 4 | 4 | 4 | 4 | 4 | 4 | 6 | 6 | 4 | 4 |
| 4 | (4,4,4,6,6) | $0.3^3 \times 0.7^2$ | 4 | 4 | 4 | 4 | 4 | 4 | 6 | 6 | 6 | 6 |
| 5 | (4,4,6,4,4) | $0.3^4 \times 0.7$ | 4 | 4 | 4 | 4 | 6 | 6 | 4 | 4 | 4 | 4 |
| 6 | (4,4,6,4,6) | $0.3^3 \times 0.7^2$ | 4 | 4 | 4 | 4 | 6 | 6 | 4 | 4 | 6 | 6 |
| 7 | (4,4,6,6,4) | $0.3^3 \times 0.7^2$ | 4 | 4 | 4 | 4 | 6 | 6 | 6 | 6 | 4 | 4 |
| 8 | (4,4,6,6,6) | $0.3^2 \times 0.7^3$ | 4 | 4 | 4 | 4 | 6 | 6 | 6 | 6 | 6 | 6 |
| 9 | (4,6,4,4,4) | $0.3^4 \times 0.7$ | 4 | 4 | 6 | 6 | 4 | 4 | 4 | 4 | 4 | 4 |
| 10 | (4,6,4,4,6) | $0.3^3 \times 0.7^2$ | 4 | 4 | 6 | 6 | 4 | 4 | 4 | 4 | 6 | 6 |
| 11 | (4,6,4,6,4) | $0.3^3 \times 0.7^2$ | 4 | 4 | 6 | 6 | 4 | 4 | 6 | 6 | 4 | 4 |
| 12 | (4,6,4,6,6) | $0.3^2 \times 0.7^3$ | 4 | 4 | 6 | 6 | 4 | 4 | 6 | 6 | 6 | 6 |
| 13 | (4,6,6,4,4) | $0.3^3 \times 0.7^2$ | 4 | 4 | 6 | 6 | 6 | 6 | 4 | 4 | 4 | 4 |
| 14 | (4,6,6,4,6) | $0.3^2 \times 0.7^3$ | 4 | 4 | 6 | 6 | 6 | 6 | 4 | 4 | 6 | 6 |
| 15 | (4,6,6,6,4) | $0.3^2 \times 0.7^3$ | 4 | 4 | 6 | 6 | 6 | 6 | 6 | 6 | 4 | 4 |
| 16 | (4,6,6,6,6) | $0.3 \times 0.7^4$ | 4 | 4 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 |
| 17 | (6,4,4,4,4) | $0.3^4 \times 0.7$ | 6 | 6 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| 18 | (6,4,4,4,6) | $0.3^3 \times 0.7^2$ | 6 | 6 | 4 | 4 | 4 | 4 | 4 | 4 | 6 | 6 |
| 19 | (6,4,4,6,4) | $0.3^3 \times 0.7^2$ | 6 | 6 | 4 | 4 | 4 | 4 | 6 | 6 | 4 | 4 |
| 20 | (6,4,4,6,6) | $0.3^2 \times 0.7^3$ | 6 | 6 | 4 | 4 | 4 | 4 | 6 | 6 | 6 | 6 |
| 21 | (6,4,6,4,4) | $0.3^3 \times 0.7^2$ | 6 | 6 | 4 | 4 | 6 | 6 | 4 | 4 | 4 | 4 |
| 22 | (6,4,6,4,6) | $0.3^2 \times 0.7^3$ | 6 | 6 | 4 | 4 | 6 | 6 | 4 | 4 | 6 | 6 |
| 23 | (6,4,6,6,4) | $0.3^2 \times 0.7^3$ | 6 | 6 | 4 | 4 | 6 | 6 | 6 | 6 | 4 | 4 |
| 24 | (6,4,6,6,6) | $0.3 \times 0.7^4$ | 6 | 6 | 4 | 4 | 6 | 6 | 6 | 6 | 6 | 6 |
| 25 | (6,6,4,4,4) | $0.3^3 \times 0.7^2$ | 6 | 6 | 6 | 6 | 4 | 4 | 4 | 4 | 4 | 4 |
| 26 | (6,6,4,4,6) | $0.3^2 \times 0.7^3$ | 6 | 6 | 6 | 6 | 4 | 4 | 4 | 4 | 6 | 6 |
| 27 | (6,6,4,6,4) | $0.3^2 \times 0.7^3$ | 6 | 6 | 6 | 6 | 4 | 4 | 6 | 6 | 4 | 4 |
| 28 | (6,6,4,6,6) | $0.3 \times 0.7^4$ | 6 | 6 | 6 | 6 | 4 | 4 | 6 | 6 | 6 | 6 |
| 29 | (6,6,6,4,4) | $0.3^2 \times 0.7^3$ | 6 | 6 | 6 | 6 | 6 | 6 | 4 | 4 | 4 | 4 |
| 30 | (6,6,6,4,6) | $0.3 \times 0.7^4$ | 6 | 6 | 6 | 6 | 6 | 6 | 4 | 4 | 6 | 6 |
| 31 | (6,6,6,6,4) | $0.3 \times 0.7^4$ | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 4 | 4 |
| 32 | (6,6,6,6,6) | $0.7^5$ | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 |

transfer nodes. Let $N$ denotes the total number of bus stations, denoted as $B_1, B_2, \ldots, B_N$. Among these, $M$ stations are located adjacent to subway stations and thus serve as transfer nodes. We denote this subset by $B_{s1}, B_{s2}, \ldots, B_{sM}$, where $1 \le s1 < s2 < \cdots < sM \le N$. Figure 1 provides an illustrative example of a coupled subway and bus network. There are a total of 11 bus stations, denoted as $B_1, B_2, \ldots, B_{11}$, among which $B_2, B_4, B_6, B_8, B_{10}$ are transfer stations connected to the subway line.

In a given period, the travel demand from station $B_i$ to $B_j$ is denoted as $D_{ij}$, where $1 \le i < j \le N$. We further assume the bus capacity between adjacent stations $B_i$ and $B_{i+1}$ is $C_i$, and the subway capacity between adjacent transfer stations $B_{sk}$ and $B_{s(k+1)}$ is $E_{sk}$. If the total travel demand between all origin-destination pairs can be fully accommodated by the bus or subway network, the system is considered **reliable**.

The reliability of such system can be evaluated through the following steps:

1. Collect historical data or distribute questionnaires to estimate the distribution of $D_{i,j}$, and use multinomial distribution to denote the distribution of $D_{i,j}$.

2. For each combination of $D_{i,j}$, check whether the system is reliable. The following scenarios may appear:

   (a) From the combination of $D_{i,j}$, calculate the

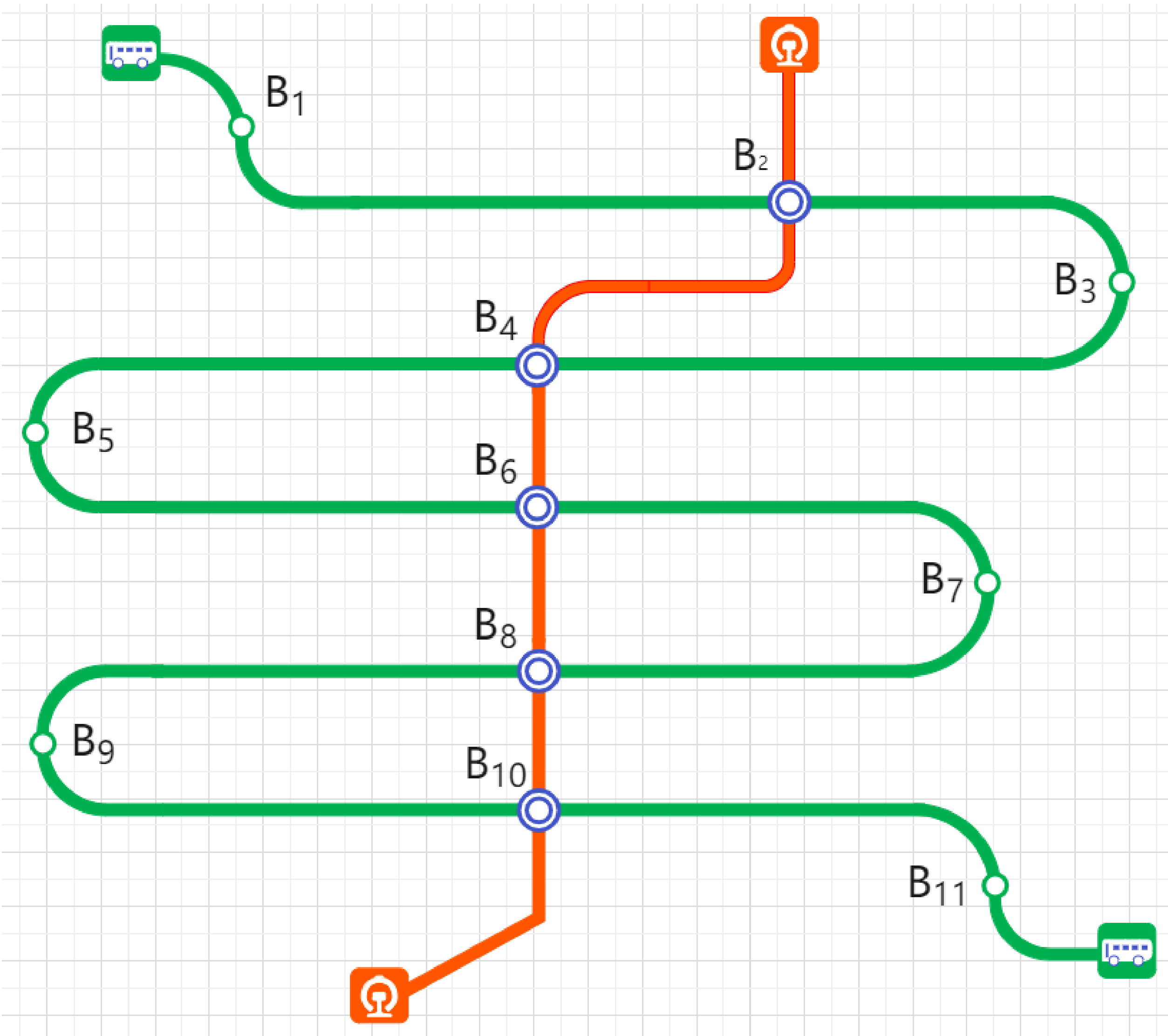


**Figure 1.** Schematic diagram of a coupled subway and bus network.

load of the section between $B_i$ and $B_{i+1}$, denoted as $G_i$, by summing up all the $D_{i,j}$ for $j > i$.

(b) Calculate the load of the subway line between $B_{sk}$ and $B_{s(k+1)}$ as $H_{sk}$, where

$$H_{sk} = \min(E_{sk}, G_{sk}, \ldots, G_{s(k+1)-1}).$$

(c) From $G_1, G_2, \ldots, G_{N-1}$, obtain the remaining load for all bus sections as $V_1, V_2, \ldots, V_{N-1}$, by deducting $H_{sk}$ from $G_{sk}, \ldots, G_{s(k+1)-1}$ for $k = 1, \ldots, M$.

(d) If $(V_1, V_2, \ldots, V_{N-1}) \leq (C_1, C_2, \ldots, C_{N-1})$, the system is assumed to be reliable. Otherwise, the system fails.

3. Sum the probabilities of all combinations for which the system is reliable to obtain the system reliability.

## 4 Numerical Study

We establish the study by letting $D_{1,3}, D_{3,5}, D_{5,7}, D_{7,9}, D_{9,11}$ follow the same binary distribution, taking the value 4 with probability 0.3 and 6 with probability 0.7. Meanwhile, let $E_2 = E_4 = E_6 = E_8 = 3$, and $C_1 = 6, C_2 = \cdots = C_8 = 3, C_9 = 2, C_{10} = 6$. Based on 2a in section 3, there are total 32 combinations of $G_1, G_2, \ldots, G_{10}$, as listed in Table 1. Figure 2 illustrates the configuration of the coupled subway and bus network used in the numerical study.

Following the steps in 2b, 2c, and 2d, sequentially process the 32 cases in Table 1 to obtain Table 2.

In Table 2, cases 1, 3, 5, 7, 9, 10, 11, 13, 15, 17, 19, 21, 23, 25, 27, 29 are reliable. Thus, the system reliability can

**Table 2.** Reliability evaluation.

| *Case No.* | *(D1,3, D3,5, D5, 7, D7,9, D9,11)* | *Probability* | *(G1,..., G10)* | *(H2, H4, H6, H8)* | *(V1,..., V10)* | *Whether the system is reliable* |
|---|---|---|---|---|---|---|
| 1 | (4,4,4,4,4) | $0.3^5$ | (4,4,4,4,4,4,4,4,4,4) | (3,3,3,3) | (4,1,1,1,1,1,1,1,1,4) | Y |
| 2 | (4,4,4,4,6) | $0.3^4 \times 0.7$ | (4,4,4,4,4,4,4,4,6,6) | (3,3,3,3) | (4,1,1,1,1,1,1,1,3,6) | N |
| 3 | (4,4,4,6,4) | $0.3^4 \times 0.7$ | (4,4,4,4,4,4,6,6,4,4) | (3,3,3,3) | (4,1,1,1,1,1,3,3,1,4) | Y |
| 4 | (4,4,4,6,6) | $0.3^3 \times 0.7^2$ | (4,4,4,4,4,4,6,6,6,6) | (3,3,3,3) | (4,1,1,1,1,1,3,3,3,6) | N |
| 5 | (4,4,6,4,4) | $0.3^4 \times 0.7$ | (4,4,4,4,6,6,4,4,4,4) | (3,3,3,3) | (4,1,1,1,3,3,1,1,1,4) | Y |
| 6 | (4,4,6,4,6) | $0.3^3 \times 0.7^2$ | (4,4,4,4,6,6,4,4,6,6) | (3,3,3,3) | (4,1,1,1,3,3,1,1,3,6) | N |
| 7 | (4,4,6,6,4) | $0.3^3 \times 0.7^2$ | (4,4,4,4,6,6,6,6,4,4) | (3,3,3,3) | (4,1,1,1,3,3,3,3,1,4) | Y |
| 8 | (4,4,6,6,6) | $0.3^2 \times 0.7^3$ | (4,4,4,4,6,6,6,6,6,6) | (3,3,3,3) | (4,1,1,1,3,3,3,3,3,6) | N |
| 9 | (4,6,4,4,4) | $0.3^4 \times 0.7$ | (4,4,6,6,4,4,4,4,4,4) | (3,3,3,3) | (4,1,3,3,1,1,1,1,1,4) | Y |
| 10 | (4,6,4,4,6) | $0.3^3 \times 0.7^2$ | (4,4,6,6,6,6,4,4,6,6) | (3,3,3,3) | (4,1,3,3,3,3,1,1,3,6) | Y |
| 11 | (4,6,4,6,4) | $0.3^3 \times 0.7^2$ | (4,4,6,6,4,4,6,6,4,4) | (3,3,3,3) | (4,1,3,3,1,1,3,3,1,4) | Y |
| 12 | (4,6,4,6,6) | $0.3^2 \times 0.7^3$ | (4,4,6,6,6,4,6,6,6,6) | (3,3,3,3) | (4,1,3,3,3,1,3,3,3,6) | N |
| 13 | (4,6,6,4,4) | $0.3^3 \times 0.7^2$ | (4,4,6,6,6,6,4,4,4,4) | (3,3,3,3) | (4,1,3,3,3,3,1,1,1,4) | Y |
| 14 | (4,6,6,4,6) | $0.3^2 \times 0.7^3$ | (4,4,6,6,6,6,4,4,6,6) | (3,3,3,3) | (4,1,3,3,3,3,1,1,3,6) | N |
| 15 | (4,6,6,6,4) | $0.3^2 \times 0.7^3$ | (4,4,6,6,6,6,6,6,4,4) | (3,3,3,3) | (4,1,3,3,3,3,3,3,1,4) | Y |
| 16 | (4,6,6,6,6) | $0.3 \times 0.7^4$ | (4,4,6,6,6,6,6,6,6,6) | (3,3,3,3) | (4,1,3,3,3,3,3,3,3,6) | N |
| 17 | (6,4,4,4,4) | $0.3^4 \times 0.7$ | (6,6,4,4,4,4,4,4,4,4) | (3,3,3,3) | (6,3,1,1,1,1,1,1,1,4) | Y |
| 18 | (6,4,4,4,6) | $0.3^3 \times 0.7^2$ | (6,6,4,4,4,4,4,4,6,6) | (3,3,3,3) | (6,3,1,1,1,1,1,1,3,6) | N |
| 19 | (6,4,4,6,4) | $0.3^3 \times 0.7^2$ | (6,6,4,4,4,4,6,6,4,4) | (3,3,3,3) | (6,3,1,1,1,1,3,3,1,4) | Y |
| 20 | (6,4,4,6,6) | $0.3^2 \times 0.7^3$ | (6,6,4,4,4,4,6,6,6,6) | (3,3,3,3) | (6,3,1,1,1,1,3,3,3,6) | N |
| 21 | (6,4,6,4,4) | $0.3^3 \times 0.7^2$ | (6,6,4,4,6,6,4,4,4,4) | (3,3,3,3) | (6,3,1,1,3,3,1,1,1,4) | Y |
| 22 | (6,4,6,4,6) | $0.3^2 \times 0.7^3$ | (6,6,4,4,6,6,4,4,6,6) | (3,3,3,3) | (6,3,1,1,3,3,1,1,3,6) | N |
| 23 | (6,4,6,6,4) | $0.3^2 \times 0.7^3$ | (6,6,4,4,6,6,6,6,4,4) | (3,3,3,3) | (6,3,1,1,3,3,3,3,1,4) | Y |
| 24 | (6,4,6,6,6) | $0.3 \times 0.7^4$ | (6,6,4,4,6,6,6,6,6,6) | (3,3,3,3) | (6,3,1,1,3,3,3,3,3,6) | N |
| 25 | (6,6,4,4,4) | $0.3^3 \times 0.7^2$ | (6,6,6,6,4,4,4,4,4,4) | (3,3,3,3) | (6,3,3,3,1,1,1,1,1,4) | Y |
| 26 | (6,6,4,4,6) | $0.3^2 \times 0.7^3$ | (6,6,6,6,4,4,4,4,6,6) | (3,3,3,3) | (6,3,3,3,1,1,1,1,3,6) | N |
| 27 | (6,6,4,6,4) | $0.3^2 \times 0.7^3$ | (6,6,6,6,4,4,6,6,4,4) | (3,3,3,3) | (6,3,3,3,1,1,3,3,1,4) | Y |
| 28 | (6,6,4,6,6) | $0.3 \times 0.7^4$ | (6,6,6,6,4,4,6,6,6,6) | (3,3,3,3) | (6,3,3,3,1,1,3,3,3,6) | N |
| 29 | (6,6,6,4,4) | $0.3^2 \times 0.7^3$ | (6,6,6,6,6,6,4,4,4,4) | (3,3,3,3) | (6,3,3,3,3,3,1,1,1,4) | Y |
| 30 | (6,6,6,4,6) | $0.3 \times 0.7^4$ | (6,6,6,6,6,6,4,4,6,6) | (3,3,3,3) | (6,3,3,3,3,3,1,1,3,6) | N |
| 31 | (6,6,6,6,4) | $0.3 \times 0.7^4$ | (6,6,6,6,6,6,6,6,4,4) | (3,3,3,3) | (6,3,3,3,3,3,3,3,1,4) | N |
| 32 | (6,6,6,6,6) | $0.7^5$ | (6,6,6,6,6,6,6,6,6,6) | (3,3,3,3) | (6,3,3,3,3,3,3,3,3,6) | N |

be denoted by

$$\begin{aligned} P = &\, 0.3^5 + (0.3^4 \times 0.7) + (0.3^4 \times 0.7) + (0.3^3 \times 0.7^2) \\ &+ (0.3^4 \times 0.7) + (0.3^3 \times 0.7^2) + (0.3^3 \times 0.7^2) \\ &+ (0.3^3 \times 0.7^2) + (0.3^2 \times 0.7^3) + (0.3^4 \times 0.7) \\ &+ (0.3^3 \times 0.7^2) + (0.3^3 \times 0.7^2) + (0.3^2 \times 0.7^3) \\ &+ (0.3^3 \times 0.7^2) + (0.3^2 \times 0.7^3) + (0.3^2 \times 0.7^3) \\ &= 0.2412. \end{aligned}$$

Note that the computed system reliability may be insufficient for practical applications. In such cases, increasing capacity on the bus or subway (or both) should be considered to raise overall reliability.

## 5 Conclusion and Future Work

This paper develops a probability-based method for assessing the reliability of a coupled subway and bus system. The reliability is defined as the probability that all trips can be served under uncertain demand and section-level capacity limits, while reflecting a subway-first travel behavior. The framework proceeds from modeling the demand distribution to sequential load calculation and capacity allocation across road and rail, and it pinpoints the demand combinations and bottleneck sections that trigger system failure. Numerical experiments show that even with seemingly moderate mean demand, tight coupling between demand volatility and section capacities can depress overall reliability far below expectation. This finding highlights the

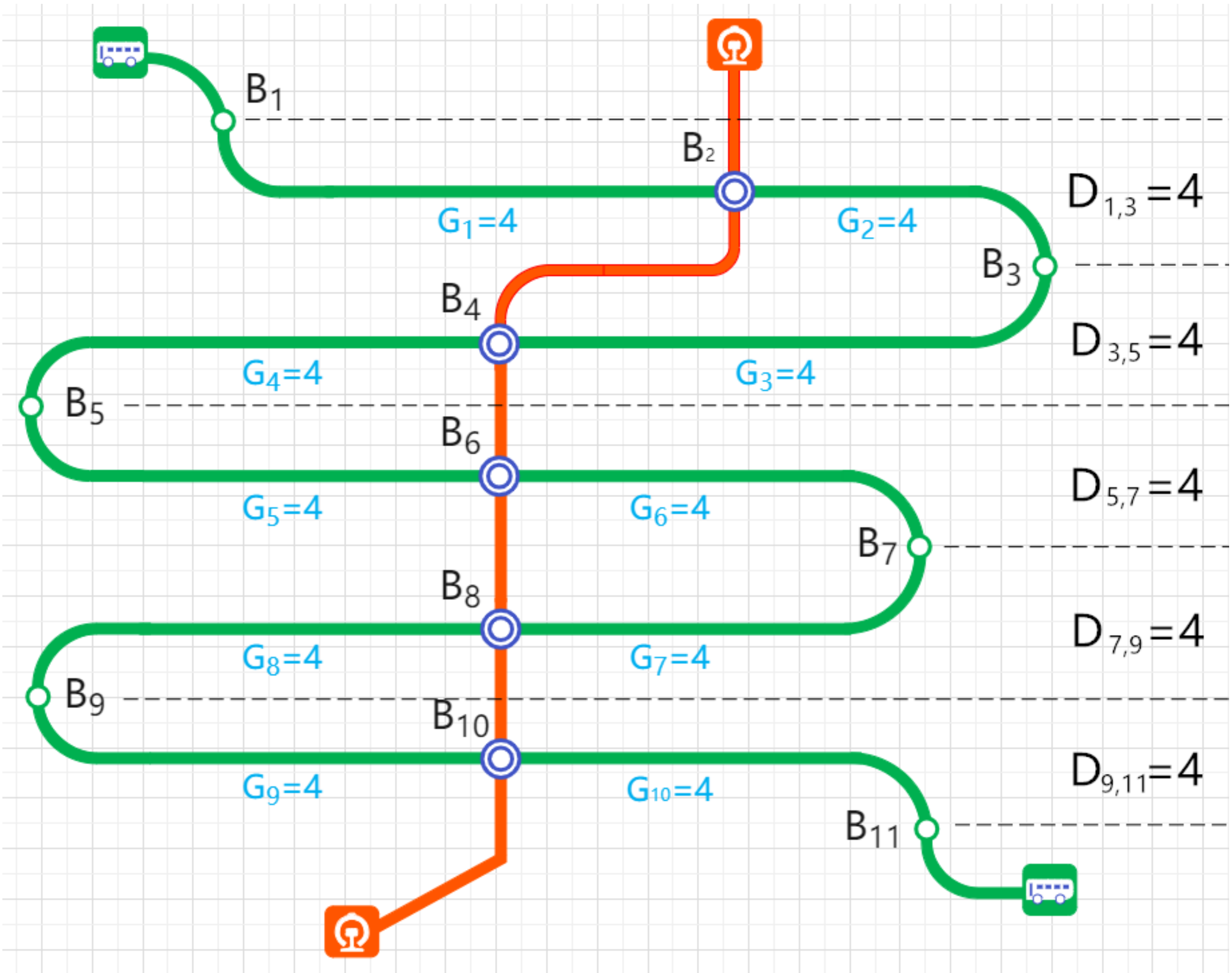


**Figure 2.** Configuration used in the numerical study.

importance of accounting for randomness rather than relying solely on average values during planning. Theoretically, the study formalizes system reliability for a two-mode coupled network with behavioral preferences and capacity constraints and offers a tractable computation procedure that reveals how coupling and variance shape outcomes. Practically, it provides a diagnostic tool that supports targeted capacity upgrades on specific subway sections or bus links, enabling cost-effective interventions to raise network reliability.

The framework can be extended in several directions. First, extend the framework to settings where bus priority and subway priority coexist and may switch with time of day, demand level, or local congestion, so that passengers choose the primary mode in a state dependent way. Second, generalize the model from a single pair of lines to realistic networks with multiple subway lines and multiple bus lines, including interline transfers, shared hubs, and overlapping service corridors. Third, promote empirical studies using real data such as smart card transactions, automatic vehicle location, and station crowding sensors to calibrate demand distributions, validate reliability estimates, and evaluate policy interventions in practice.

## Data Availability Statement

Data will be made available on request.

## Funding

This work was supported without any funding.

## Conflicts of Interest

The authors declare no conflicts of interest.

## AI Use Statement

The authors declare that no generative AI was used in the preparation of this manuscript.

## Ethical Approval and Consent to Participate

Not applicable.

## References


[1] Ahmed, S., & Dey, K. (2020). Resilience modeling concepts in transportation systems: a comprehensive review based on mode, and modeling techniques. *Journal of Infrastructure Preservation and Resilience, 1*(1), 8. [CrossRef]

[2] Chen, A., Yang, H., Lo, H. K., & Tang, W. H. (2002). Capacity reliability of a road network: an assessment methodology and numerical results. *Transportation Research Part B: Methodological, 36*(3), 225-252. [CrossRef]

[3] Bešinović, N. (2020). Resilience in railway transport systems: a literature review and research agenda. *Transport Reviews, 40*(4), 457–478. [CrossRef]

[4] Ceder, A. (2016). *Public transit planning and operation: Modeling, practice and behavior*. CRC Press. [CrossRef]

[5] Chen, C., Wang, S., Zhang, J., & Gu, X. (2023). Modeling the vulnerability and resilience of interdependent transportation networks under multiple disruptions. *Journal of Infrastructure Systems, 29*(1), 04022043. [CrossRef]

[6] Du, Y., Wang, H., Gao, Q., Pan, N., Zhao, C., & Liu, C. (2022). Resilience concepts in integrated urban transport: a comprehensive review on multi-mode framework. *Smart and resilient transportation, 4*(2), 105-133. [CrossRef]

[7] Guo, X., Du, Q., Li, Y., Zong, X., & Bai, L. (2025). Cascading failure and recovery propagation of metro-bus double-layer network under time-varying passengers. *Transportation Research Part D: Transport and Environment, 139*, 104571. [CrossRef]

[8] Hosseini, A., & Pishvaee, M. S. (2022). Capacity reliability under uncertainty in transportation networks: An optimization framework and stability assessment methodology. *Fuzzy Optimization and Decision Making, 21*(3), 479–512. [CrossRef]

[9] Hu, Z., Yang, J., Chang, S., & Zhang, Y. (2025). Robustness analysis of bus-rail multilayer network based on dynamic passenger flow. *Reliability Engineering & System Safety, 264*, 111403. [CrossRef]

[10] Bell, M. G., & Iida, Y. (1997). *Transportation network analysis*. John Wiley & Sons. [CrossRef]

[11] Li, J. Y., Teng, J., & Wang, H. (2025). Measuring robustness in uncertain topologies: a study of on-demand bus networks. *Transportmetrica A: Transport Science, 21*(3), 2317783. [CrossRef]

[12] Liu, B., Liu, X., Yang, Y., Chen, X., & Ma, X. (2023). Resilience assessment framework toward interdependent bus–rail transit network: Structure, critical components, and coupling mechanism. *Communications in Transportation Research, 3*, 100098. [CrossRef]

[13] Liu, Y., Yang, T., & Su, J. (2025). Optimal bus bridging service for urban rail transit disruptions with stochastic passenger demand. *PLoS One, 20*(10), e0333686. [CrossRef]

[14] Shen, Y., Yang, H., Ren, G., & Ran, B. (2024). Model cascading overload failure and dynamic vulnerability analysis of facility network of metro station. *Reliability Engineering & System Safety, 242*, 109711. [CrossRef]

[15] Sun, Y. (2020). Fuzzy approaches and simulation-based reliability modeling to solve a road–rail intermodal routing problem with soft delivery time windows when demand and capacity are uncertain. *International Journal of Fuzzy Systems, 22*(7), 2119–2148. [CrossRef]

[16] Wang, N., Wu, M., & Yuen, K. F. (2023). A novel method to assess urban multimodal transportation system resilience considering passenger demand and infrastructure supply. *Reliability Engineering & System Safety, 238*, 109478. [CrossRef]

[17] Wen, X., Si, B., Wei, Y., & Cui, H. (2025). Resilience assessment of urban rail transit systems: A literature review. *Public Transport*, 1–25. [CrossRef]

[18] Lam, W. H., Gao, Z. Y., Chan, K. S., & Yang, H. (1999). A stochastic user equilibrium assignment model for congested transit networks. *Transportation Research Part B: Methodological, 33*(5), 351-368. [CrossRef]

[19] Xing, J., Yin, X., Zhang, J., & Chen, J. (2023). Resilience modeling and improvement of metro systems considering statistical behaviors of passenger mobility. *International Journal of Disaster Risk Reduction, 96*, 103975. [CrossRef]

[20] Yuan, Y., Li, S., Liu, S. Q., D'Ariano, A., & Yang, L. (2025). Dynamic bus bridging strategy in response to metro disruptions integrated with routing, timetabling and vehicle dispatching. *Omega, 134*, 103287. [CrossRef]

[21] Zhang, J., Ren, G., & Song, J. (2023). Resilience-based optimization model for emergency bus bridging and dispatching in response to metro operational disruptions. *PLoS One, 18*(3), e0277577. [CrossRef]

[22] Zhang, L., Xu, M., & Wang, S. (2023). Quantifying bus route service disruptions under interdependent cascading failures of a multimodal public transit system based on an improved coupled map lattice model. *Reliability Engineering & System Safety, 235*, 109250. [CrossRef]

[23] Zhang, S., Lo, H. K., Ng, K. F., & Chen, G. (2021). Metro system disruption management and substitute bus service: a systematic review and future directions. *Transport Reviews, 41*(2), 230–251. [CrossRef]

[24] Maltinti, F., Melis, D., & Annunziata, F. (2012). Road network vulnerability: A review of the literature. *ICSDC 2011: Integrating Sustainability Practices in the Construction Industry*, 677-685. [CrossRef]

**Kaiye Gao** Professor at Beijing Forestry University. His research focuses on system reliability and risk management. In recent years, he has published or had accepted over 60 academic papers and has led or participated in 24 research projects. (Email: kygao@foxmail.com)

**Rongquan Yu** Graduated Master's students from Beijing University of Technology. (Email: 15801102250@163.com)

**Sicheng Zhang** Master's student at the School of Economics and Management, Beijing University of Technology. (Email: 488438829@qq.com)

**Di Wu** Assistant Professor at the Central University of Finance and Economics. His research focuses on system reliability and maintenance. In recent years, he has published or had accepted more than 10 academic papers. (Email: blessudwu@gmail.com)