Optimizing Tailored Bus Bridging Paths

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1. INTRODUCTION

Due to unexpected events, such as infrastructure malfunctions, accidents and extreme weather conditions, metro disruptions frequently occurred in recent years throughout the world. For instance, severe metro disruptions in Barcelona in August 2008, London in August 2010, Shanghai in September 2011, Singapore in December 2011 and Beijing in August 2016 interrupted the travel plans of many passengers.

Bus bridging service is widely used during metro disruptions. It connects the disrupted metro system with buses dispatched from depots. Various studies have been advanced to the optimization of bus bridging strategy (*1-5*). However, the main drawback is that they generally assumed that buses operate on predetermined bridging routes with specific frequencies. With limited bus resources, the resulting bus bridging service may not be able to handle the outbursts of passenger demand efficiently given the frequency requirement and the constraint that one bus could only operate on one route.

Optimizing a tailored bridging path for each bus to follow may result in more efficient bus bridging service. We consider the Bus Bridging Problem (BBP) from the perspective of Vehicle Routing Problem (VRP) and develop a two-stage integer linear programming formulation to optimize a tailored bridging path for each bus to follow. A path depicts the stations that a bus should visit in sequence once it is dispatched from the depot. The affected metro stations, reserved buses, bus capacity, passenger demands and bus travel times are considered in the optimization. The objective of the model considers the needs of metro agency and passengers. The first priority is to minimize the maximum bus bridging time, which is the time when all stranded passengers are transported to their destination stations or a turnover station. The second priority is to minimize average passenger delay to reduce the negative impacts of disruptions on passengers. The advantage of the proposed model is demonstrated in a case study based on the metro network in Rotterdam, The Netherlands.

Our approach has the potential for real-life application with the rapidly growing usage of new technologies. For example, transit agency could get the information of passenger demands via Automated Fare Collection (AFC) data or mobile phone data so that they can make decisions for the bus bridging operation. They could also obtain real-time bus locations via automatic vehicle location technology and give instructions to buses via wireless communication technologies. The introductions could be displayed on on-board screens for bus drivers to follow. Passengers could obtain real-time information of the buses they could take via apps on smartphones or variable message signs at stations. Then they can decide to either use the bridging service or continue their journey by other means.

2. METHODOLOGY

Consider a part of a metro network in Figure 1, where part of the network around station S4 is out of service due to infrastructure malfunctions. The influence of the disruption extends to the nearest turnover stations for each direction, where track crossover is available. Only beyond the turnover stations can the metro line operate in short routing mode. Therefore, the whole metro network is disrupted, including both the metro line segments from station S1 to station S6 and from station S7 to station S10. Passengers are stranded at affected stations. There are two bus depots D1 and D2 with buses reserved nearby.

The BBP is to provide bus service for stranded passengers in disrupted metro area with limited bus resources from bus depots such that they could continue their journey. Passenger demands are described by origin-destination (OD) flow matrix, including demands between turnover stations, between turnover and disrupted stations and between disrupted stations. The demands originated from or destined to a turnover station are actually an aggregation for all stations beyond the turnover station.

To simplify the problem, two assumptions are made: (1) passenger demands and bus travel times are known and constant; (2) buses have the same and fixed capacity. Instead of predetermining bridging routes and assigning buses to routes with given frequencies like previous studies, we propose a flexible bus bridging strategy to assign tailored bridging paths to buses. Take Bus 2 in Figure 1 as an example, the tailored bridging path for it is D2→S8→S5→S6→S9. Tailored bridging paths are often non-intuitive as shown in Figure 1. The bridging service is completed when all buses complete their respective bridging paths.

A bus is assumed to only upload passengers destined to its next destined station when it arrives at a station. The loading rule is applicable since passengers waiting at the station ought to be informed of the arriving times and the next destined stations of coming buses, rather than the bridging path of each bus. For each bus, dispatching station is defined as the metro station it is dispatched to from the depot and a trip is defined as the movement from one metro station to another.

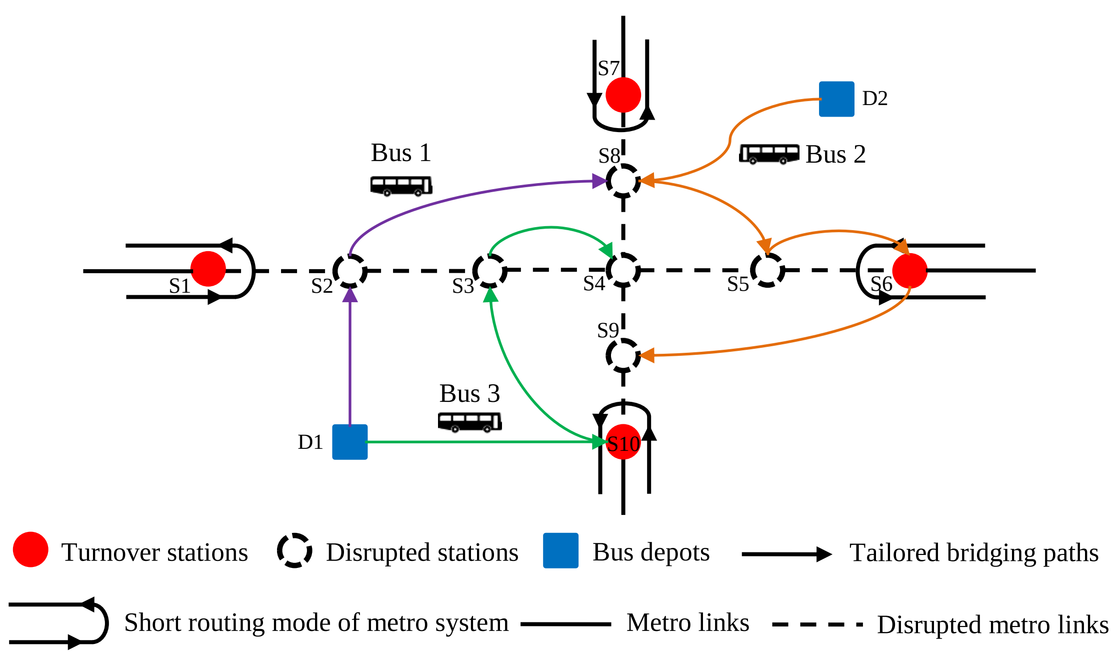

FIGURE 1 Description of the Bus Bridging Problem.

In this study, we propose a two-stage integer linear programming model to determine tailored bridging paths for buses. The objectives of the two stages are constructed from the perspectives of metro agency and passengers, respectively. Stage I determines key components of the tailored bridging paths with the objective of minimizing the time to transport all stranded passengers to their destination stations or turnover stations, which is equivalent to minimizing the maximum bus bridging time. Decision variables for each bus include the dispatching station and number of trips it travels from one station to another. To reduce passenger costs incurred by the disruption, Stage II further details the tailored bridging paths with the objective of minimizing average passenger delay. Decision variables for each bus include the stations that a bus should visit in sequence, as illustrated in Figure 1. The integer linear programs of the proposed two-stage model are solved with the MIP solver in CPLEX (*6*) with the YALMIP interface (*7*).

3. FINDINGS

The proposed strategy is validated in a hypothetical case based on the metro network of Rotterdam, The Netherlands. A traditional strategy often used by transit agencies in response to such disruptions is used for comparison purpose. In the traditional strategy, first a shortest route is found to connect all affected stations. Then each bus is dispatched to the nearest station in the disrupted area and travels along the shortest route, *i.e.*, makes roundtrips between the first and the last stations of the shortest route. The bus visits each station to unload and load passengers. The maximum bridging time for traditional strategy is defined as the time when all passengers reach their destination stations or turnover stations.

3.1 Case settings

The case settings are described as follows. Six stations were shut down due to disruption (see Figure 2). Stations 1, 2, 3 and 6 are turnover stations for crossover. Twelve buses reserved in two surrounding depots which match the reality are dispatched to provide bus bridging service. We used an agent-based multimodal dynamic network simulation tool based on (*8*) to count the number of passengers that use the considered metro segments during a period of one hour in case of no disturbance – and, assuming no rerouting, would thus strand in a disruption lasting one hour – constructing an OD matrix for bus bridging from those counts. From the same simulation, we also recorded the travel times in the road network between each pair of stations and from the bus depots to each station. In the simulation, we include signalized intersections, configured with the Webster method, and fundamental diagrams with subcritical delays and capacity drops (*9*). The multimodal network, including train/metro/tram/bus timetables, are derived from the static model of the municipality for the year 2015; the demand data originates from the activity-based Albatross model (*10*) for a working day in the year 2004, with correction factors to match household and trip counts for 2015.

FIGURE 2 Disrupted area in metro network of Rotterdam, The Netherlands.

3.2 Results and analyses

Table 1 presents the maximum bus bridging time and average passenger delay resulting from both the proposed and traditional strategies. It reveals that the proposed strategy completes the transportation of all stranded passengers in shorter time and result in lower passenger delay. In traditional strategy, buses run in predesigned bridging route, resulting in larger bridging time and passenger delay. By assigning a tailored bridging path to each bus, the proposed strategy reduces the maximum bridging time and average passenger delay by 102 and 47 min, respectively.

TABLE 1 Maximum Bus Bridging Time and Average Passenger Delay (unit: min)

Strategy / Performance measure	Proposed strategy	Traditional strategy
Maximum bridging time	106	208
Average passenger delay	61	108

Advantage of our proposed strategy exists not only in its aggregated level but also in each station. Table 2 presents bridging time and average delay at each station. It can be shown that the proposed strategy outperforms the traditional strategy at every station. The maximum bridging time and average delay for all stations of the proposed strategy are 106 min and 70 min, respectively. They are even smaller than minimum bridging time and average delay for all stations of the traditional strategy, which are 127 min and 81 min, respectively.

TABLE 2 Performance Measures for Each Station in Proposed and Traditional Strategies

(a) Maximum Bus Bridging Time (unit: min)

Station / Strategy	Station 1 Eendrachtsplein	Station 2 Stadhuis	Station 3 Blaak	Station 4 Beurs	Station 5 Leuvehaven	Station 6 Wilhelminaplein
Proposed strategy	106	106	106	106	70	106
Traditional strategy	181	127	208	185	158	131

(b) Average Passenger Delay (unit: min)

Station / Strategy	Station 1 Eendrachtsplein	Station 2 Stadhuis	Station 3 Blaak	Station 4 Beurs	Station 5 Leuvehaven	Station 6 Wilhelminaplein
Proposed strategy	55	70	62	49	29	65
Traditional strategy	128	81	131	127	136	84

4. CONCLUSIONS

In this study, we propose a flexible bus bridging strategy to maintain passengers' journey in the affected stations during disruptions of metro networks. Unlike existing literatures to design bus routes and then allocate buses to predefined routes with specific frequencies, a novel bus bridging model is formulated to optimize a tailored bridging path for each bus. The proposed bus bridging strategy is formulated as a two-stage model to balance operational priorities of both transit agency and passengers. The Stage I model minimizes maximum bus bridging time while the Stage II model minimizes average passenger delay. The proposed strategy is evaluated in a case study of the metro network in Rotterdam, The Netherlands. The results indicate that the proposed strategy outperforms the traditional strategy from the perspectives of both transit agency and passengers.

The proposed model is somewhat limited by the assumption that passenger demands and travel times are not time-dependent. Further research could focus on extending the model to handle dynamic arrivals and departures of passenger as well as dynamic travel times. Also, other realism improvements such as stochastic elements in passenger demands and travel times can be considered in further research.

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