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Enhancing metro network resilience via localized integration with bus services

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A B S T R A C T

This paper advances the field of network disruption analysis by introducing an application to a multi-modal transport network, capitalizing on the redundancies and improved connectivity of an integrated metro-bus network. Metro network resilience to disruptions can be enhanced by leveraging on public bus services. To ensure better acceptance among operators and commuters, we focus on introducing localized integration with bus services instead of designing an entirely new bus network to achieve the desired resilience to potential disruptions. This is accomplished by increasing the capacity of bus services that run in parallel with affected metro lines as well as those connecting to different metro lines. Our analysis starts with a network representation to model the integrated metro and bus system. A two-stage stochastic programming model is further developed to assess the intrinsic metro network resilience as well as to optimize the localized integration with bus services. The approach is applied to a case study based on the Singapore public transit system and actual travel demand data. The results show that the metro network resilience to disruptions can be enhanced significantly from localized integration with public bus services.

1. Introduction

Metro systems have been acting as a key solution for supporting mobility needs in high-density urban areas. Being a mode of shared transportation service, metro systems carry large quantity of commuters in a more environmentally friendly manner than private transport. The dependence on metro systems keeps growing in many cities over the world. Take Singapore as an example, a city with a population of 5 million generated around 1 million metro trips per day in 2011. Such a heavy dependence imposes enormous strains on metro systems and makes service disruptions hardly affordable. Even limited service disruptions in metro systems could result in significant productivity loss and widespread confusion. Take the 16th December 2011 disruption in Singapore's metro network for example: train services at 11 stations were disrupted for 5 h and more than 100,000 commuters were affected. Thus, the reliability of metro network and its resilience to potential disruptions should be well ensured.

Resilience of a system refers to the ability to withstand disruptions within acceptable reduction in service performance. In the context of metro systems, the resilience could be measured by the loss of capacity and the service level recovery efforts for disruption responses. Instead of relying on post-disruption recovery operations (e.g., running bus bridging services), a more effective way is to improve the intrinsic resilience so that possible disruptions (within a certain disruption scale) incur

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Nomenclature

Sets:

W	set of origin–destination (OD) pairs
Ω	set of disruption scenarios
$\mathcal{N}_M$	set of metro node
$\mathcal{A}_M$	set of metro arcs
$\mathcal{N}_B$	set of bus node
$\mathcal{A}_B$	set of bus arcs, union of parallel bus arc set $\mathcal{A}_B^1$ and inter-line bus arc set $\mathcal{A}_B^2$
$\mathcal{A}_T$	set of transfer arcs
$\mathcal{N}$	$\mathcal{N} = \mathcal{N}_M \cup \mathcal{N}_B$
$\mathcal{A}$	$\mathcal{A} = \mathcal{A}_M \cup \mathcal{A}_B \cup \mathcal{A}_T$
K_w	set of feasible paths in the metro-bus network for OD pair w
B	set of bus lines
P_b	set of localized integration plans for a certain bus line b
Ψ_b	$\Psi_b := P_b \times P_b$, set of integration plans that cannot be introduced simultaneously for bus line b

Parameters:

ζ	the resilience of a metro network
d_w	amount of travel demand that is satisfied under disruption condition between OD pair w
D_w	total travel demand for OD pair w under normal condition
(ρ_i^1, ρ_i^2)	representation of a node with ρ_i^1 and ρ_i^2 indicating the metro station and travel mode, respectively
c_{ij}	service capacity (maximum number of commuters per hour) of arc $(i,j) \in \mathcal{A}$
t_{ij}	travel/transfer time of arc $(i,j) \in \mathcal{A}$
(u_w, v_w)	origin and destination nodes of OD pair w
β_w	maximum travel time increase allowed for OD pair w
T_w^0	journey time of OD pair w when no disruption occurs
c_b	the hourly spare service capacity of bus line b that can be used by metro commuters during disruptions
θ_{ij}^b	1 if bus arc (i,j) is covered by the current bus line b; and 0 otherwise
δ_{pij}	1 if bus arc (i,j) is newly covered in the integration plan p; and 0 otherwise
$\delta_{pij'}$	1 if the currently covered bus arc (i,j) is removed in the integration plan p; and 0 otherwise
$\Delta c_{ij}(\xi)$	the capacity reduction on arc $(i,j) \in \mathcal{A}_M$ under disruption scenario $\xi \in \Omega$
γ_{wij}^k	1 if arc (i,j) is used by the kth shortest path of OD pair w; and 0 otherwise
q_i^1	the commuter in-flow capacity for station i
q_i^2	the commuter out-flow capacity for station i
$\Delta q_i^1(\xi)$	the reduction of metro node in-flow capacity under disruption scenario ξ for station i
$\Delta q_i^2(\xi)$	the reduction of metro node out-flow capacity under disruption scenario ξ for station i
$Z(\xi)$	the fraction of travel demand fulfillment under disruption scenario ξ
L_1^b	maximum number of employed integration adjustments for bus line b
q_p^b	additional number of buses needed if localized integration plan p for bus line b is introduced
L_2	number of additional buses available
φ_{wik}^1	1 if commuter flow w on path k belongs to the in-flow of the metro station i; and 0 otherwise
φ_{wik}^2	1 if commuter flow w on path k belongs to the out-flow of the metro station i; and 0 otherwise
p_ξ	the weight of disruption scenario ξ

Decision variables:

x_{ij}^k	1, if arc (i,j) belongs to the kth shortest path; 0, otherwise
y_p^b	1, if the localized integration plan $p \in P_b$ of bus line b is selected; 0, otherwise
$f_w^k(\xi)$	$\geqslant 0$. The commuter flow of OD pair w on path k under disruption scenario ξ

minimum performance reduction or even no negative impact ideally. Measures of improving metro network resilience include (1) building a well-connected network with self-adaptive ability to recover from disruptions, and (2) integrating metro and bus systems in such a way that bus system provides as much backup capacity as possible during metro disruptions. The