The Value of New Cross-Radial Links for Public Transport Network Resilience

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ABSTRACT

The introduction of new links to network topology could potentially contribute to greater capability to withstand system breakdowns. This paper analyses the value of adding new cross-radial links for public transport network resilience. The value is evaluated in terms of passenger welfare under disruptions. Using a model that considers passengers’ dynamic travel choices, stochastic traffic conditions, timetables and capacity constraints, a new light rail transit line in Stockholm, Sweden is evaluated. The results show that the cross-radial link reduces the impacts of disruptions of critical links; the total value of resilience is positive and significantly offsets the loss in welfare caused by disruption of the cross-radial link itself.

INTRODUCTION

To handle the challenges of congestion, noise and emissions facing many urban areas, the shift of travel from personal cars to public transport options is generally seen as one of the most important strategies (e.g., European Council, 2006). To achieve this, the public transport system needs to be competitive under ideal operating conditions, but also resilient (robust, non-vulnerable), that is, able to withstand or quickly recover from disturbances such as infrastructural and vehicular malfunctions and planned maintenance closures.

Public transport networks (PTN) are characterized by multiple layers: At the bottom there are the physical infrastructure networks of roads and railways, on which networks of public transport lines are operated. In the top layer travellers create networks of trips connecting origins, destinations and transfer nodes. The importance of transfers, multimodality, transport hubs and intermediate walking links means that PTN are quite complex; however, the connectivity is in general lower than for road networks, and the level of service varies non-continuously according to timetables. The impacts of service disruptions depend on local crowding levels as well as on how the demand reacts to changes in supply. Depending on its duration, a disruption may also impact service availability upstream and even on other lines due to its impact on vehicle scheduling.
The focus of this paper is the influence of network design on PTN resilience. Roth et al. (2012) showed that the world’s largest subway networks share a very similar structure (network topology), with a central core from which branches radiate. Meanwhile, previous studies have suggested that network topology has effects on PTN resilience. It is well-known that the connectivity of radial networks is highly vulnerable to disruption, isolating one branch from the remaining network. Derrible and Kennedy (2010) suggested that robustness of subway systems corresponds to the number of cyclic paths available in the network, representing the possibility to use alternative routes under disruption.

Graph theory provides various measures of link importance that were applied on PTN worldwide (von Ferber et al., 2009, 2012). These studies considered the number of immediate connections (node degree) and the betweenness centrality measure which corresponds to the share of shortest paths between nodes which go via a certain node. They concluded that network connectivity in terms of the size of the largest connected subset is more sensitive to disruptions targeted on betweenness centrality than those attacks directed towards high node degree. The same conclusion was reached when vulnerability was defined in terms of the speed in which the system becomes fragmented (Colak et al., 2010). Notwithstanding, PTN varied with respect to the impact of various attack scenarios (von Ferber et al., 2012).

This paper analyzes the effects on PTN resilience when new cross-radial infrastructural and/or operational links are added to a largely radial network. According to network theory, such new links should increase the connectivity and the redundant capacity in the network, thereby increasing the resilience (e.g., Derrible and Kennedy, 2010). This logic is sometimes used as an argument for building new infrastructural links. In practice, however, passengers are likely to adjust their travel patterns and expectations according to the existence of the new links. The net impact on resilience is thus less than obvious, in particular when considering that the new link may itself be disrupted.

The analysis is based on the dynamic, stochastic and multimodal notion of PTN vulnerability, taking into account the dynamic variations and interactions between supply and demand, introduced by Cats and Jenelius (2013). A probabilistic path choice process is used to model passenger decisions, where the evaluation of alternative paths depends on passenger’s preferences and perceptions. The impact of link disruption is evaluated as the reduction in welfare (considering travel time, number of transfers, etc.) due to the disruption. The methodology is applied in a real-world case study for the high frequency PTN of Stockholm, Sweden and the introduction of a cross-radial light rail line. To evaluate the public transport system performance under varying conditions, a dynamic public transport operations and assignment model, BusMezzo, is used (Cats, 2013).

METHODOLOGY

The dynamic, stochastic and multimodal PTN model used in this study is described in detail in Cats and Jenelius (2013). In brief, public transport lines operate on the physical infrastructure network between specific origin-destination (OD) terminal nodes. Riding times on links vary between days depending on traffic conditions, and
dwell times at stops depend on the number of boarding and alighting passengers. The
departure time of a vehicle trip depends on the arrival time of the preceding trip.
Travel demand is defined between pairs of OD nodes and each trip is realized as a
path of links between a node pair. The probability of choosing a specific path is speci-
fied as a discrete choice model and depends on the properties of the different lines
and on the conditions a given day, according to the preferences of the individual.

The model allows the performance of the system to be evaluated in terms of
passenger welfare, essentially the total utility of the passengers expressed in monetary
terms. Since travel demand levels and line schedules may vary with time, so do the
impacts of network disruption. Day-to-day variations in demand and supply further
imply that the impacts are stochastic. In a dynamic setting, an important aspect of a
disruption is the recovery time, that is, the time from the beginning of the disruption
until the system has recovered to operating normally again. The recovery time will
vary between scenarios and is determined by the dynamic interactions of supply and
demand.

To evaluate the impacts of a disruption scenario $\sigma$, it is therefore sufficient to
compare the total welfare $W(\sigma)$ with that in the associated baseline scenario $\sigma_0$, $W(\sigma_0)$. The impact is thus

$$\Delta W(\sigma) = W(\sigma) - W(\sigma_0).$$  \hspace{1cm} (1)

In the case study of this paper, welfare is evaluated as a generalized cost func-
tion which is a linear combination of four factors: in-vehicle time, waiting time,
walking time and number of transfers.

The focus of this paper is on two dimensions of the scenarios: the network
configuration that is available, i.e., the baseline configuration or with some set of new
links built, and the network element that is disrupted, i.e., the set of disrupted links
and nodes. Other factors such as the start time and duration of the disruption are held
fixed in all scenarios. A disruption scenario $\sigma$ involving network configuration $n$ and
disrupted network element $\delta$ can then be summarized as the pair $\sigma = (n, \delta)$. Let $n_0$ denote the baseline network with no new links, and let $\delta = 0$ denote a scenario with
no disruption. In this framework, the value of new link set $n$ under normal operating
conditions is

$$\Delta W(n \mid n_0) = W(0,n) - W(0,n_0),$$  \hspace{1cm} (2)

while the impact of disruption scenario $\delta$ in network configuration $n$ is

$$\Delta W(\delta \mid n) = W(\delta,n) - W(0,n).$$  \hspace{1cm} (3)

The value of new links $n$ for the resilience against disruption of element $\delta$, finally, is

$$VNL(n \mid \delta) = \Delta W(\delta \mid n) - \Delta W(\delta \mid n_0)$$
$$= [W(\delta,n) - W(0,n)] - [W(\delta,n_0) - W(0,n_0)].$$  \hspace{1cm} (4)
In the case study the value of a new cross-radial line (link set) is evaluated for a set of severe link disruption scenarios.

APPLICATION

Stockholm rapid public transport network

The method for evaluating the impact of new links on network resilience is applied to the Stockholm rapid transit network. The city is built on fourteen islands and bridges constitute bottlenecks in the transport system. The rapid PTN – services that operate with an average scheduled headway up to 5 minutes during the morning peak period – consists of metro, trunk bus lines and a light rail train. The latter is the subject of analysis in this case study.

The public transport system of Stockholm is characterized by a highly radial structure, as is clearly visible in Figure 1. The metro network consists of seven lines which form three trunks (Blue line: 10-11; Red line: 13-14; Green line 17-19). Stockholm metro network has a radial structure that supports high regional accessibility, low degree of connectivity and mid-level of directness when compared with other metro systems in the world (Derrible and Kennedy 2010). The metro system is well-known for its transit-oriented development along satellite suburbs developed around far-reaching line branches. The three main metro trunks intersect only at one station (T-Centralen) and three additional stations allow transferring between two trunks (Fridhemsplan, Slussen and Gamla Stan). This network structure generates bottlenecks along the three metro trunks where branches merge and lines intersect. Bus trunk lines provide high coverage in the inner-city where the metro system has limited local accessibility.

A new cross-radial line

In 2002 a light rail transit (LRT) line, Line 22, was launched in order to provide better connections between the southern and western suburbs (see Figure 1). The line functions as a cross-radial line (CRL) that connects major interchange stations (Gullmarsplan, Liljeholmen and Alvik) with the Green and Red Lines. The orbital line provides a new connection between hubs that are strategically located along the southern and western edges of the inner city. Moreover, it allows passengers to travel between the southern and western parts of Stockholm without going through the oversaturated city centre line segments and transfer hubs. The CRL was constructed with varying types of right-of-way along its corridor including mixed traffic, dedicated tramways and completely elevated tracks. The line is 11.5 km long and serves 17 stops. In 2014 a further extension towards the northern suburbs will provide connections to the Blue Line branches.

The development of the CRL project is part of Stockholm’s strategic vision to extend the inner-city boundaries to its edges and stimulate the development of a more polycentric urban area. In addition, the investment in CRL was motivated by its ability to provide new travel alternatives that will relieve the congestion from the most
critical metro segments. The availability of alternative connections could be particularly valuable in case of service disruptions. The purpose of this application is to assess the impact of the CRL project on network resilience.

Figure 1. Stockholm’s rail-based public transport network (source: SLL)

Scenario design

The scenario design consists of a combination of network configuration and service disruption scenarios. We consider the metro and trunk bus line network prior to the opening of the CRL ($n_0 = S$), and with the CRL service ($n = S + L$). Figure 2 presents two representations of the network graph where nodes correspond to either stops or transfer hubs and links to line segments.

A choice-set generation model was performed for each network configuration. The generation process performs a path search technique subject to filtering and dominance rules. Paths are then merged to hyperpaths based on common stops and lines along the path. The procedure resulted with 120,346 for the enhanced network ($S + L$) compared with 96,834 alternative hyperpaths for the baseline network ($S$). These path-sets were then used as background choice-sets in the dynamic path choice model implemented in BusMezzo.

The PTN operations were simulated for the morning peak period (06:00-09:00), while passenger assignment was simulated only during the rush hour (07:00-
08:00) in order to allow warm-up and cleaning periods. Each public transport mode is simulated with distinguished vehicle types, vehicle capacity, operating speed, traffic regime, dwell time function and control strategies. These set of operational attributes yields different reliability and capacity levels depending on service design and right-of-way. Given the service frequency, travellers are assumed to depart randomly from the origins without consulting timetables. The case study PTN consists of 437 stops and has 700 public transport services which are assigned to 200 vehicles during the morning peak period.

An OD matrix was constructed by applying an iterative proportional fitting method based on a base OD matrix and passenger counts data that were available from the metropolitan public transport agency. A total of approximately 125,000 individual passenger trips are generated during the rush-hour. Passengers are assumed to have prior-knowledge concerning planned headways and scheduled travel times. Real-time information concerning the next expected arrival time is provisioned at each stop across the network.

The performance of both networks was analyzed under normal operations and severe service disruptions. Note that normal operations account for various sources of uncertainty inherent to the public transport operations environment. Service disruptions were simulated by introducing a link closure on a set of critical links. Such a closure could be caused in practice due to technical failures, vehicle breakdown (in the case of rail-bound infrastructure) or a terror threat. The closure start time was set to 07:15 and lasted for 30 minutes. During the breakdown period vehicle queue up upstream and passengers cannot alight from these vehicles. The simulation model captures the cascading upstream and downstream effects as well as potential spilling effects caused by vehicle trip chaining and passengers rerouting decisions.

Service disruptions were simulated on sets of consecutive links that were identified through a generalized measure of passenger betweenness centrality accounting for the dynamic, stochastic PTN model. The procedure described in Cats and Jenelius (2013) found that the following two line segments are among the most critical segments in the case study network (see Figure 2):

- Liljeholmen-Slussen (bi-directional), Red Line - lines 13 and 14 ($\delta = R$)
- Alvik-Fridhemsplan (bi-directional), Green Line - lines 17,18 and 19 ($\delta = G$)

The construction of the CRL is expected to contribute to the PTN resilience by providing alternative connections in case of service disruption. However, the CRL itself might also be subject to disruptions and hence impose additional risk for system performance in case of service failure. An additional disruption scenario was hence simulated for the network with the CRL ($\delta = L$). Note that the scenario of normal operations without the CNL service, $\sigma = (S, 0)$, differs from the scenario with a breakdown of the CNL service, $\sigma = (S + L, L)$ in two fundamental respects. First, the CRL service is fully available prior to the breakdown start time and gradually recovers following the breakdown removal. Second, passengers travel decisions are based on a different set of network prior knowledge and real-time information provision. The dynamic representation of PTN operations and passengers route choice makes it possible to distinguish between these two scenarios.
In order to obtain robust outputs, the stochastic simulation model requires the analysis of a number of simulation replications. All of the reported results are averaged over ten simulation replications which obtained a maximum allowable error of 1%. The execution time for a single run was less than 1 minute on a standard PC.

**Results**

Passenger travel times were analysed for each scenario by considering the entire population of passengers. Figure 3 decomposes the generalized travel time into the in-vehicle, wait, walk and transfer components. It is evident that in-vehicle time is the largest travel time component in all scenarios although it does not dominate the generalized travel time. The value-of-time of in-vehicle time incorporates the impact of crowding based on the guidelines provided in the meta-analysis by Wardman and Whelan (2011). In-vehicle time is followed by waiting time and transfer penalty. The average in-vehicle and waiting time components decrease in the presence of CRL, in particular in the case of a disruption on the Red Line. In contrast, walking time and the transfer penalty components remained almost unchanged following the introduction of CRL. A breakdown of the CRL leads to an increase in the in-vehicle time to the same level as it was prior to its introduction, while the waiting time rises beyond the original level.
The total travel times in absolute terms as well as the total generalized travel time are summarized in Table 1. In addition, the table presents the average welfare impact per passenger. An average reduction (increase) of 1 welfare unit per passenger is equivalent to a loss (gain) of approximately 100,000 Swedish Crowns (15,000$) for all passengers during a single rush hour. The CRL leads to an increase of 2.21% in total welfare, which worth approximately 150,000 Swedish Crowns during a single rush hour. Note that these gains refer only to demand originating and destined along the base case network (S) and hence do not account for demand generated elsewhere, including along the CRL corridor or induced demand due to the introduction of a new service.

Service disruptions cause a considerable reduction in total welfare. Disruptions on the critical Red and Green segments results with a welfare loss between 4.7-7.6 welfare units or 7-11% of the total welfare, compared with normal operations on the respective network. This is a considerable loss for a breakdown that lasts 30 minutes. The negative impact of the disruption is lower in all cases for the network that includes CRL. The last column of Table 1 shows that the CRL connection contributes to network resilience due to the possibility to bypass the disrupted link. The CRL helps mitigating the impact of the disruption, in particular in the case of a disruption on the Red Line.

Finally, the CRL could itself be subject to service breakdowns. A disruption on the CRL results in a considerable welfare loss (1.81 units or 2.76%), although significantly lower than a breakdown of a critical segment. The welfare during the disruption is lower than in the undisrupted network without CRL. In other words, passengers’ reliance on the CRL leads to a welfare loss compared to if it was non-existent in the first place. However, the welfare loss is similar in magnitude to the value of the CRL for resilience against one of the critical disruption scenarios, and significantly smaller compared to the other disruption scenario. In total, the CRL thus
contributes positively to resilience, at least if the frequency of disruptions on the CRL itself is not significantly higher than for other links.

Table 1. Passenger travel time and welfare consequences for each scenario

| Scenario σ | Total travel time [sec] | Total generalized travel time [sec] | Welfare $W(n, \delta)$ | Welfare impact of disruption $\Delta W(\delta | n)$ | Value of new link for resilience $VNLR(n | \delta)$ |
|------------|-------------------------|-----------------------------------|------------------------|---------------------------------|---------------------------------|
| Baseline network |
| $(S, 0)$ | 958 | 1684 | -67.12 |
| $(S, G)$ | 1020 | 1812 | -72.03 | -4.91 |
| $(S, R)$ | 1056 | 1888 | -74.72 | -7.60 |
| Cross-radial line |
| $(S + L, 0)$ | 952 | 1643 | -65.64 |
| $(S + L, G)$ | 1017 | 1765 | -70.38 | -4.73 | +1.66 |
| $(S + L, R)$ | 1006 | 1777 | -70.87 | -5.23 | +3.85 |
| $(S + L, L)$ | 961 | 1692 | -67.45 | -1.81 |

CONCLUSION

The paper analyzed the value of adding new cross-radial links (CRL) for public transport network resilience, evaluated in terms of passenger welfare under disruptions. Using a model that considers passengers’ dynamic travel choices, stochastic traffic conditions, timetables and capacity constraints, a new light rail transit line in Stockholm, Sweden was evaluated. The results show that the CRL reduces the impacts of disruptions of critical links; the total value of resilience is positive and significantly offsets the loss in welfare caused by disruption of the CRL itself.

A natural extension of the presented framework is to incorporate resilience effects into the economic appraisal (e.g., cost-benefit analysis) of new infrastructure projects. This requires further research on two aspects: First, the frequency with which each disruption scenario occurs should be incorporated, and the appraisal should be based on the cumulative welfare loss over all disruptions. Second, rather than considering only the most critical links, a more exhaustive set of disruption scenarios should be used, so that the total value for resilience across various possible scenarios is reflected.

Another interesting direction for further research is the incorporation of resilience aspects in network design. While this paper studied the value of a given set of new links in an existing network, one could test alternative network structures. A potential approach could iteratively add/remove links as a method to test optimal network evolution (Ash and Newth, 2007).
REFERENCES


