Vulnerability of Collaborative Transport Networks

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1 INTRODUCTION

To offer a wider range of transport options and reduce costs, transport companies combine their individual transport offerings through collaboration (Cruijssen *et al.*, 2007). In this paper, we focus on multi-modal container transport, which aims to provide flexible, resilient, and sustainable transport systems, and which involves the use of alternative transport modes train and barge, next to truck. In multi-modal transport, coordination efforts between carriers include sharing of booking and planning information, redistribution of costs and benefits, tracking of deliveries, and error handling.

However, successful collaborative transport is subject to a number of conditions, among which are competitive and commercial alignment, organizational readiness, and sufficient technical infrastructure. If these conditions are not met, collaboration may not yield the expected benefits and can even be prone to failure. In particular, impacts such as legislative (antitrust) or policy changes, conflicts, technical failure, or cyber-attacks can lead to the collapse of collaborative systems with adverse impact on the transportation performance. Offering multi-modal services in hinterland transport, for instance, requires extensive alignment, synchronization, and planning between carriers and terminal operators, with an increasing need for decision support (Agamez-Arias & Moyano-Fuentes, 2017). Indeed, vertical collaboration does not only manifests itself at the physical level, where containers are transshipped between modes of transport, but also at the collaboration level through connected systems. As a result, there is a growing need to consider vulnerabilities of transport systems beyond those of the physical systems and include vulnerabilities of the highly interdependent collaborative (information) systems that are progressively used in multi-modal transportation.

Carriers that are involved in collaboration are also players in transportation markets (Saeedi *et al.*, 2017). As a result, they oftentimes collaborate with competitors. As we will see in this paper, the way that disruptions impact the performance of the transportation system is also informed by the market structure.

In this paper, we will use complex network models to analyze vulnerabilities emerging from collaborative transportation and we will present results. In particular, we model transportation systems with vertical collaboration between carriers, who each operate their own proprietary network of transport services. In this system, carriers have the possibility to establish dyadic collaborations, enabling them to provide shared sequential transportation chains including transshipments. Transportation services and collaborations between carriers are represented in networks on two separate network layers. The collaboration layer comprises carriers as nodes and their dyadic collaborations as edges. The physical layer is defined by edges representing transportation services associated with the operating carrier, and nodes representing transshipment points, e.g. ports or inland terminals. Our focus is on vertical collaboration with consecutive transportation services and transshipments.

Vulnerabilities are defined by the risks and impacts of disruptions on network performance. We focus here on disruptions at the collaboration level. For instance, while coordinating multimodal transport chains, carriers depend on each other for the quality of exchanged information on service schedules, bookings, available capacities, transshipment plannings, and so on. We assume that disruptions are triggered at individual carriers, i.e. disruptions occur at the nodes in the collaboration layer.

We develop an integrated transportation-collaboration model to analyze vulnerabilities that emerge from large-scale collaborative transportation systems. Our model derives relationships between risks emerging from bilateral carrier collaborations and general system characteristics such as market structure. The model is sophisticated enough to capture the complex interdependencies between transport services and carrier collaborations including the associated transport performance. At the same time, it is simple enough to be applied to large random networks and allow for the systematic assessment of the impact of varying network structures on vulnerability. We show that the market structure of carriers, i.e., the disparity in number of services operated, has a non-monotone impact on vulnerability in case of targeted disruption of carrier collaborations.

2 THE MODEL

The network model in this paper has two network layers as depicted in Figure 1. The first layer describes the physical network, in which multi-modal paths are established through vertical collaboration between carriers, who each operate their own proprietary network of transport services. The connectivity of the transport layer depends on the presence of links in the collaboration layer. While carrier B can offer shared transport routes with both other carriers, carriers A and C can only do that with carrier B, but not with each other. As a result, connection 1-2-5 (if 1-2 is operated by carrier A) and 4-6-5 are not feasible, despite the existence of transport services on these connections. The effect of disruption is twofold. Failure of collaboration links leads to more infeasible connections, however not all collaboration links are equally critical to transport functionality. If A-B fails, it would cause more impact than if B-C fails, since A-B enables a higher number of multi-carrier paths. Moreover, since disruption is assumed to happen to carriers, causing them to lose all their collaboration links, disruption at carrier B would be most severe causing the loss of both existing collaboration links.

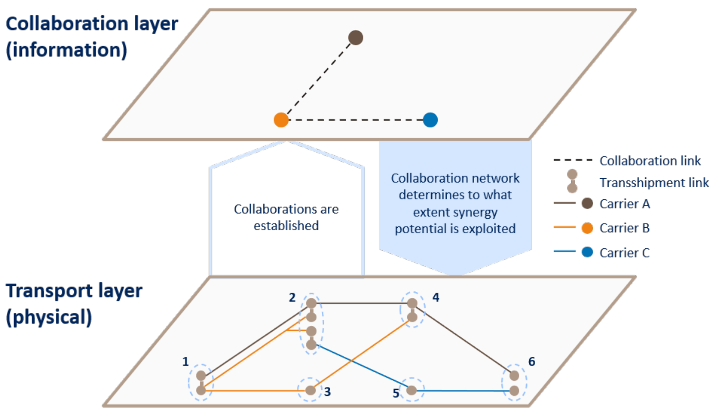


Figure 1 – *Two-layered network model*

Formally, the transport network $G^T = (V^T, E^T)$ consists of a set V^T of transshipment areas as nodes and a set E^T of transport services as edges. Each edge $e \in E^T$ is attributed to a carrier $c \in V^C$ that operates the service. The same pair of nodes can be served by multiple carriers, which makes G^T a multi-graph with parallel edges. The second layer $G^C = (V^C, E^C)$ describes the collaborations between carriers. The edge set E^C represents dyadic collaborations between carriers. We write $N^T = |V^T|$ and $N^C = |V^C|$.

We study the impact of market structure on vulnerability, while using two random network classes serving complementary purposes. The first probabilistic network class, solely described by a set of parameters without the need for generating actual networks, allows for an analytical evaluation and is therefore suitable to establish general relationships between market structure and vulnerability. The second network class is based on simulations, and is more representative of real-world collaborative transportation systems.

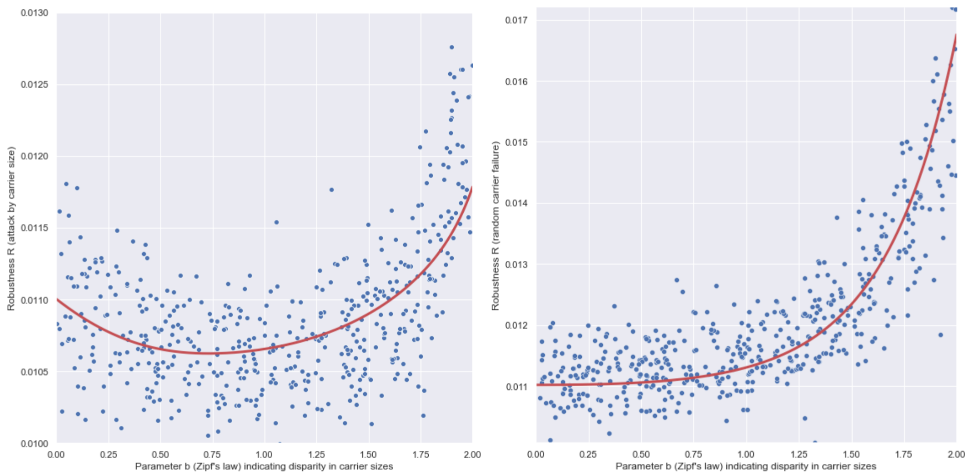
A general characteristic found across different types of real-world transport networks, e.g. air transport or public transport networks, is the scale-free property, i.e. a degree distribution following a power law $P(k) \sim k^{-\gamma}$ with few high-degree nodes (hubs) and many low-degree nodes. The setup of analytically tractable probabilistic random networks is less straightforward. There are limitations in calculating foundational metrics such as the expected average shortest paths, given that not every path is feasible depending on the presence of collaborations. Therefore, we resort to Erdos-Renyi networks $G(N^T, p)$, i.e., random network with Poisson distributed degrees, with N^T nodes and a fixed probability p of the existence of an edge between any pair of nodes. Each carrier $c \in V^C$ operates a service on each edge with probability p_c.

Lack of collaboration limits the set of possible paths given by the transport layer. A disrupted carrier can still operate its own services in the transport network, but loses the ability to offer transshipment connections with other carriers, i.e. only single-carrier routes are available for this carrier. We assume that, in absence of disruptions, a link between two carriers in the collaboration networks exists as soon as there is at least one transshipment point between services of the two carriers in the transport layer. Therefore, all transshipments are feasible and paths can be formed without collaborative restrictions. Since the underlying physical network is an Erdos-Renyi network, the collaboration probability $p^{\kappa}_{c_1 c_2} = p^{\kappa}$ is a constant parameter for two different carriers ($c_1 \neq c_2$), while $p^{\kappa}_{c_1 c_2} = 1$ if $c_1 = c_2$. As a result, the collaboration layer itself is equivalent to an Erdos-Renyi network $G(N^C, p^{\kappa})$. Given the assumptions on physical and collaboration layer structure with constant p and p^{κ}, each potential transshipment is independent and feasible with a constant probability $p^{\theta} = 1 - \prod_{q \neq r}(1 - p^{\kappa} p_{c_q} p_{c_r}) \prod_q (1 - p^2_{c_q})$, which combines multiple relevant parameters into a single one. In this manner, we capture both the structure of the collaboration network and transshipment constraints in a collaborative system. With Erdos-Renyi network layers, the network can be fully described by $G(N^T, p, p^{\theta})$ as p^{θ} is a function of p^{κ} and p_c.

Two measures are used to quantify the impact of collaborative transport on system performance. First, efficiency is measured by the average (intermodal) path length over all OD pairs in the transportation network $G = (V, E)$, given by $\phi^{sp}(G) = \frac{1}{N(N-1)} \sum_{(i,j) \in E} d(i,j)$. For disconnected graphs this measure obviously conveys a falsely positive measure. Therefore, we define robustness $\phi(G) = \frac{1}{N(N-1)} \frac{|E|}{\phi^{sp}(G)}$, where we use the reciprocal value of the shortest paths. Collaborative transport aims at reducing the average path length, and thereby increasing robustness. We adopt the robustness measure $R = \frac{1}{N^C+1} \sum_{u=0}^{N^C} \phi(u)$ from Schneider *et al.* (2011) that takes the average of ϕ at various levels of disruption, i.e., where a progressive number of carriers in the collaborative layer are disrupted. So, the robustness measure describes how the average path length across the network increases as a result of failing connections.

3 RESULTS

We model different market structures by means of Zipf's law, a discrete version of the power law, where the relative frequency of the i-th element in a given set of N^C ranked elements is given by $f(i, b, N^C) = i^{-b} (\sum_{j=1}^{N^C} j^{-b})^{-1}$. Synergies in joint route planning are moderated by the market structure of carriers, i.e. they are highest if there is a large number of small or medium-sized flow-controlling entities (Cruijssen *et al.*, 2007). However, the obvious conclusion that systems



(a) *R under targeted disruption* (b) *R under random disruption*

Figure 2 – *Robustness under varying market structure*

become more vulnerable the more they are distributed would be myopic. Vulnerability is not only about the potential magnitude of functionality loss represented by the difference in functionality between a fully-collaborative and a non-collaborative scenario, but also about susceptibility to disruption, i.e. to what extent can certain types of disruption exploit the dependence on collaboration and realize a functionality loss. Susceptibility to random and targeted disruption in a complex network depends on the distribution of node criticality. For instance, networks with few dominating nodes, corresponding with a centralized market structure in collaborative transport, are highly susceptible to targeted disruption (Albert *et al.*, 2000).

Figure 2 shows the robustness R for a routing constrained network with $N^T = 200$, $p = 0.01$, $p^\kappa = 0.8$, and $N^C = 20$. The red lines present analytical results of R, which are roughly consistent with the outcomes of Monte Carlo simulations (1000 realizations), presented by blue dots. Robustness is computed based on (a) targeted disruption by carrier size and (b) random order of disruption. The graph shows that under targeted disruption, the carrier disparity does not have a monotone effect on the vulnerability of multi-carrier transport systems, but takes on a U-shape with a minimum at intermediate disparity. While centralized setups (high b) with one or few dominant carriers are most robust to disruption, and fully distributed setups (low b) exhibit decent robustness as well, intermediate setups (intermediate b) with both larger and smaller carriers are most vulnerable with a minimum around $b = 0.75$. In the case of random disruption (Fig. 2 (b)), the result is in turn monotone.

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