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Development of Network-Based Measures and Computational Methods for Evaluating the Redundancy of Transportation Networks

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1. INTRODUCTION

1.1 Research Subject and Motivation

Natural and man-made disasters encountered over the past decade have repeatedly emphasized the importance of transportation networks and the need for government agencies and communities to make the transportation system more resilient. Events such as the 9/11 terrorist attacks in 2001, the London bombing in 2005, Hurricanes Katrina and Rita in 2005, Minneapolis' I-35W bridge collapse in 2007, New Zealand's earthquake in 2011, Japan's devastating earthquake/tsunami in 2011, Superstorm Sandy in 2012, a typhoon and earthquake in Philippines in 2013 all contribute to this growing sense of urgency to improve the adaptability of transportation networks.

For example, the United States Department of Transportation (USDOT) has incorporated resiliency into the National Transportation Recovery Strategy (USDOT, 2009). The overall goal of this strategy is to enhance the recovery process of transportation networks under disruptions and to increase the resiliency of various infrastructures in the community. A number of conceptual and/or computational frameworks have recently been proposed to analyze resiliency. Some examples include Chang and Nojima (2001), Victoria Transport Policy Institute (2005), Tierney and Bruneau (2007), Heaslip et al. (2010), Croope and McNeil (2011), Urena et al. (2011), and Omer et al. (2013) for a general transportation network resiliency evaluation framework; Caplice et al. (2008), Ortiz et al. (2009), Ta et al. (2009), Adams and Toledo-Durán (2011), and Miller-Hooks et al. (2012) for a freight system resiliency evaluation framework, and Faturechi and Miller-Hooks (2014) for a general civil infrastructure system).

The Multidisciplinary Center for Earthquake Engineering (MCEER) provides the four "Rs" concept to characterize resiliency: robustness, redundancy, resourcefulness, and rapidity (Bruneau et al., 2003). Redundancy is defined as "the extent to which elements, systems, or other units of analysis exist that are substitutable, i.e., capable of satisfying functional requirements in the event of disruption, degradation, or loss of function." The Webster/Merriam Dictionary (2012) gives a general definition of redundancy (or the state of being redundant) as: i) exceeding what is necessary or normal, or ii) serving as a duplicate for preventing failure of an entire system upon failure of a single component. Redundancy has been widely studied and applied in many domains, such as reliability engineering (O'Connor, 2010), communications (Wheeler and O'Kelly, 1999), water distribution systems (Kalungi and Tanyimboh, 2003), and supply chain and logistics systems (Sheffi and Rice, 2005).

In transportation, some researchers have introduced various measures for assessing the resiliency of transportation networks, and redundancy is one of those measures. For example, Berdica (2002) developed a qualitative framework and basic concepts for vulnerability as well as many interconnected concepts such as resiliency and redundancy. According to Berdica (2002), redundancy is the existence of numerous optional routes/means of transport between origins and destinations that can result in less serious consequences in case of a disturbance in some part of the system. The Federal Highway Administration (FHWA, 2006) defined redundancy as the ability to utilize backup systems for critical parts of the system that fail. They emphasized that it is extremely important to consider redundancy in the development of a process or plan for emergency response and recovery. One of the pre-disaster planning strategies is to improve network resiliency by adding redundancy to create more alternatives for travelers or by hardening the existing infrastructures to withstand disruptions. Godschalk (2003) and Murray-Tuite (2006) defined redundancy as the number of functionally similar components that can serve the same purpose, thus the system does not fail when one component fails. Also, Goodchild *et al.* (2009) and Transystems (2011) introduced redundancy as one of the properties of freight transportation resiliency, and defined redundancy as the availability of alternative freight routes and/or modes.

Along a different line, Jenelius (2010) proposed the concept of redundancy importance and proposed two measures (i.e., flow-based and impact-based) by considering the importance of links as a backup alternative when other links in the network are disrupted. The flow-based measure considers a net traffic flow that is redirected to the backup link, and the impact-based measure considers an increased travel time (cost) due to the rerouting effect. However, these two measures only quantify the localized redundancy importance of a transportation network. In other words, they are unable to capture the diversity of alternatives, which are important properties in measuring network redundancy. The diversity of available routes needs to be explicitly considered in the redundancy characterization when the primary choice is inoperative. In summary, despite a growing body of research on resiliency, there is no formal mathematical definition of transportation network redundancy, and few researchers have concretely developed quantitative network-based measures and computational methods to assess the multifaceted characteristics of transportation network redundancy.

There are a few challenges and practical considerations associated with modeling transportation network redundancy. Adding redundancy to create more alternatives for travelers could involve not only routes but also travel modes. In addition, multiple travel modes within the system could increase the redundancy by providing substitutions to maintain transport service if one or more modes are disturbed by disruptions. For example, in the 1994 Northridge earthquake in California, the transit system helped alleviate the initial congestion in the Los Angeles highway network. During the interstate freeway reconstruction, transit usage on rail and bus lines tripled; however, it was reduced to pre-earthquake levels one year after the disruption (Deblasio et al., 2003). Hence, the redundancy measure should consider the flexibility of travel alternatives as well as the behavioral response of users in the event of a disruption. However, the alternative diversity alone may not be a sufficient measure of network redundancy as it lacks interactions between transport demand and supply. Capacity is not explicitly considered in the evaluation of travel alternatives (i.e., mode and route). Hence, it is necessary to include network capacity in measuring transportation network redundancy. Evaluating network-wide capacity is not a trivial matter. Multiple origin-destination (O-D) pairs exist, and the demands between different O-D pairs are not exchangeable or substitutable. The network-wide capacity is not just a simple sum of the individual link capacities. Also, mode and route choice behaviors have to be considered in estimating multi-modal network capacity. Disruption on an auto link may increase the travel time of auto mode or even change the availability of auto mode. This may further lead to flow shift between modes, changing the multi-modal network capacity.

1.2 Objectives

The objectives of this report are twofold: (1) to develop network-based measures for systematically characterizing the redundancy of transportation networks, and (2) to develop computational methods for evaluating the network-based redundancy measures. Travel alternative diversity and network spare capacity are developed as two quantitative measures to capture the considerations of travelers and planners (i.e., the two main decision-making stakeholders in transport systems). They can address two fundamental questions in the pre-disaster transport system evaluation and planning, i.e., “how many effective redundant alternatives are there for travelers in the event of a disruption?” and “how much redundant capacity does the network have?” In the context of a general network resiliency evaluation framework, the proposed measures of network redundancy can be considered as a critical component in assessing network resiliency and also designing a transportation network more resilient against disruptions.

On one hand, the travel alternative diversity dimension serves to evaluate the existence of multiple modes and effective routes available for travelers, or the degree of effective connections between a specific O-D pair. Travelers might not treat all simple routes as their effective alternatives. A shorter, detoured route with an acceptable travel cost (i.e., not-too-long route) is more likely to be considered by travelers as a reasonable substitution when the primary or secondary route is not available. Also, as different routes may share the same links or segments in the network, the number of routes may drop significantly when one main link fails to function. On the other hand, the network spare capacity dimension serves to quantify the network-wide capacity with an explicit consideration of travelers’ mode and route choices as well as congestion effect. These two measures can complement each other by providing a two-dimensional characterization of network redundancy from the perspective of both travelers and planners.

To implement these two network-based measures in practice, a formal methodology is provided to evaluate the transportation network redundancy. As the travel alternative diversity dimension, a node adjacent matrix operation method developed by Meng et al. (2005), is extended to count the number of effective routes (i.e., not only efficient routes but also not-too-long routes) by using a user-specified threshold. The counting results could be further used to evaluate the number of effective routes traversing a particular link and to identify the heavily overlapped links. These important modifications could enhance the assessment realism of route diversity. As to the network spare capacity dimension, we employ an optimization-based approach to explicitly determine the maximum throughput considering travelers’ mode substitution and route choice as well as congestion effect. The logit and C-logit models are used to consistently capture travelers’ mode substitution and route choice behaviors under the network equilibrium framework.

Specifically, the objectives include the following:

1. Develop network-based measures for characterizing the redundancy of transportation networks.
2. Develop computational methods for evaluating the network-based redundancy measures.
3. Collect data from different sources to develop a case study for evaluating the redundancy of a real transportation network.
4. Conduct a case study using the city of Winnipeg, Canada.

1.3 Organization of the Report

The organization of this report is summarized as follows:

- Section 2 describes the two measures with respect to network-based redundancy measures.
- Section 3 provides the computational method for evaluating network redundancy.
- Section 4 provides two numerical examples to demonstrate the desirable features of the two redundancy measures and the applicability of the evaluation methodology.
- Section 5 provides some concluding remarks and recommendations for future research.

2. NETWORK-BASED REDUNDANCY MEASURES

In this section, we characterize transportation network redundancy from two perspectives: travel alternative diversity and network spare capacity.

2.1 Travel Alternative Diversity

Travel alternative diversity refers to the existence of multiple modes and effective routes available for travelers, or the degree of effective connections between a specific O-D pair. We use K_{rs} to denote the set of available routes connecting a generic O-D pair (r,s), and $|K_{rs}|$ to denote the cardinality of this set. A route consists of a set of links, which are characterized by a zero-one variable denoting the state of each link (operating or failed). If there is only one route between an O-D pair (r,s), i.e., $|K_{rs}|=1$, the travelers from origin r cannot reach destination s when one or more links on this single route are failed under an earthquake or a severe traffic accident. Note that more available routes correspond to more opportunities of realizing the evacuation trips when encountering disastrous events. Hence, it is vital to provide multiple alternatives, particularly for an important O-D pair with a large amount of commuting trips.

The travel alternative diversity is a general concept. According to the specification of available routes, we may use simple routes, efficient routes (Dial, 1971), or distinct routes (Kurauchi et al., 2009). Even within the category of efficient routes, there are also different definitions, such as "always moving further away from the origin and closer to the destination," "always moving further away from the origin" (Dial, 1971), "either always moving further away from the origin or always moving closer to the destination" (Tong, 1990), and "efficient and not-too-long routes" (Leurent, 1997). Note that the specification of route diversity needs to explicitly consider the tradeoff between computational tractability and modeling realism. For example, it is known that there is no polynomial-time algorithm that is able to count the number of different simple routes between an O-D pair (Valiant, 1979; Meng et al., 2005). Also, counting distinct routes with acceptable travel time between each O-D pair is computationally non-trivial due to the bi-level programming structure (Kurauchi et al., 2009). On the other hand, counting the efficient routes seems computationally efficient according to the polynomial-time combinatorial algorithm of Meng et al. (2005). In view of the computational advantage, we focus on the specification of efficient routes but with two important modifications to enhance the assessment realism of route diversity.

Travelers might not treat all simple or efficient routes as their effective alternatives. A shorter, detoured route with an acceptable travel cost (i.e., not-too-long route) is more likely to be considered by travelers as a reasonable substitution when the primary or secondary route is not available. In addition, as different routes may share the same links or segments in the network, the number of routes may drop significantly when one main link fails to function. Below we model the above two requirements.

If a route includes only links that make travelers farther away from the origin, it is an efficient route (Dial, 1971). Mathematically, all links in an efficient route satisfy

$$l_r\left(\text{head}_a\right) > l_r\left(\text{tail}_a\right), \forall a \in \Gamma_k \tag{2-1}$$

where tail_a and head_a are the tail and head of link a; $l_r(\text{tail}_a)$ and $l_r(\text{head}_a)$ are, respectively, the shortest route cost from origin r to the tail and head of link a; Γ_k is the set of links on route k.

The requirement of a shorter detoured route with an acceptable cost (i.e., a not-too-long route) can be implemented in a link manner by requiring every link be reasonable enough relative to the shortest path (Leurent, 1997). Mathematically,

$$\left(1+\tau_r^a\right)\left(l_r\left(\text{head}_a\right)-l_r\left(\text{tail}_a\right)\right) \geq l_a, \ \forall a \in \Gamma_k \tag{2-2}$$

where l_a is the length or free-flow travel time of link a; τ_r^a is a maximum elongation ratio for link a with respect to origin r. τ_r^a may be set to 1.6 in inter-urban studies or between 1.3 and 1.5 in urban studies (Tagliacozzo and Pirzio, 1973; Leurent, 1997). By summing up all links on route k, we have

$$\begin{aligned} l_k = \sum_{a\in\Gamma_k} l_a &\leq \sum_{a\in\Gamma_k}\left(1+\tau_r^a\right)\left(l_r\left(\text{head}_a\right)-l_r\left(\text{tail}_a\right)\right) \\ &\leq \sum_{a\in\Gamma_k}\left(1+\tau_r^{\max}\right)\left(l_r\left(\text{head}_a\right)-l_r\left(\text{tail}_a\right)\right) \\ &= \left(1+\tau_r^{\max}\right)\left(l_r\left(s\right)-l_r\left(r\right)\right) = \left(1+\tau_r^{\max}\right)\min_p l_p \quad , \end{aligned} \tag{2-3}$$

where l_k is the length of route k; and $\tau_r^{\max} = \max_{a\in\Gamma_k} \tau_r^a$. One can see that Eq. (2-2) is at a link level, which circumvents the computationally demanding path enumeration issue. Also, it can ensure that the route length does not exceed $\left(1+\tau_r^{\max}\right)$ times of the shortest path length, as shown in Eq. (2-3).

For illustration purposes, Figure 2.1 provides an example for the not-too-long route. This simple network has one O-D pair, five links (their lengths are shown in the figure), and three routes. We look at the lower detoured link. The elongation ratio is set at 1.6. The left-hand side of Eq. (2-2) is (1+1.6)(l_r(2)-l_r(1))=2.6, which is less than the link length of 3. Hence, this link is not a reasonable link with respect to origin r.

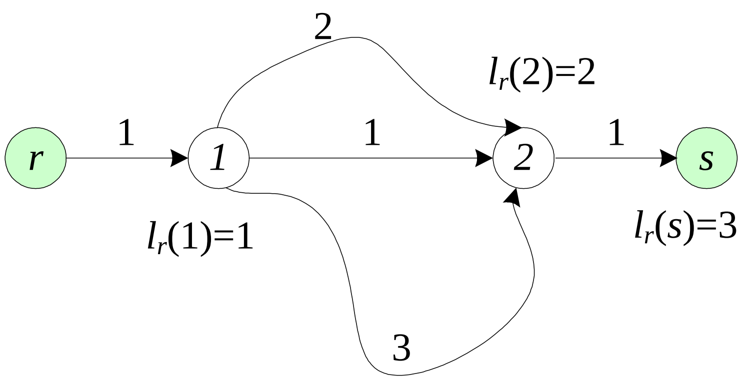

Figure 2.1 Illustration of not-too-long route

The route overlapping issue could be considered by modifying link costs. For example, a link-size factor (Fosgerau et al., 2013) or a link-based commonality factor (Russo and Vitetta, 2003) could be added to the link cost to "penalize" the link shared by multiple routes, and subsequently the check of efficient route in Eq. (2-1). However, this manner is not intuitive and it is difficult to quantify the impact of a link-size factor or link-based commonality factor. In this report, we use an indirect way to treat this requirement. Specifically, we evaluate the number of efficient routes from an O-D pair using a particular link N_a^{rs}, which is also referred to as the link multiplicity (Russo and Vitetta, 2003). This information would also assist in identifying critical links associated with network redundancy. A link used by a large number of efficient routes is obviously an important link, whose disruption will have a significant impact on the network.

Remark 1: Note that the above definition of travel alternative diversity is at an O-D pair level. In other words, we obtain an assessment on the degree of effective connections for each O-D pair. However, we can aggregate it to different spatial levels (e.g., zonal and network levels) according to different evaluation purposes. Note that the aggregation could explicitly consider the effect of travel demand on route alternative diversity. Typically, more travelers within an O-D pair need more available routes to disperse the travel demands.

2.2 Network Spare Capacity

The travel alternative diversity is assessed using only network topology characteristics. It lacks interactions between transport demand and supply. Capacity is not explicitly considered in the evaluation of travel alternatives (i.e., mode and route). Also, congestion effect and travelers' choice behavior are two critical characteristics of transportation systems. In order to adequately capture these characteristics, we consider network spare capacity as the second dimension of network redundancy. Evaluating the network-wide capacity is not trivial since it is not just a simple sum of the individual link capacities. Multiple O-D pairs exist, and the demands between different O-D pairs are not exchangeable or substitutable. Also, mode and route choice behaviors have to be considered in estimating the multi-modal network capacity. Disruption on an auto link may increase the travel time of auto mode or even change the availability of auto mode. This may further lead to flow shift between modes, changing the multi-modal network capacity.

For the network capacity model, Wong and Yang (1997) proposed the concept of reserve capacity for a signal-controlled road network. It was defined as the largest multiplier μ applied to a given existing O-D demand matrix **q** that can be allocated to a network without violating a pre-specified level of service (LOS). The largest value of μ indicates whether the current network has spare capacity or not: if μ>1, the current network has a reserve (or spare) capacity amounting to 100(μ-1) percent of **q**; otherwise, the current network is overloaded by 100(1- μ) percent of **q**. Yang et al. (2000) formulated the network capacity and level of service problem as determining the maximum zonal trip generation subject to combined trip distribution and assignment equilibrium constraints. Gao and Song (2002) extended the reserve capacity model of Wong and Yang (1997) by considering O-D pair-specific demand multipliers. Chen and Kasikitwiwat (2011) further detailed the network capacity model of Yang et al. (2000) as the ultimate and practical network capacity models.

To accommodate considerations of both mode substitution and route choice, we propose a multi-modal network spare capacity model. It quantifies the maximum throughput of a network while considering travelers' mode substitution and route choice behaviors as well as congestion effect. We use the logit model to capture the travelers' mode substitution behavior. Regarding the route choice, we adopt the C-logit model proposed by Cascetta et al. (1996) to account for similarities between overlapping routes by adding a commonality factor (CF) in the systematic utility term. The C-logit model has been used in many applications, such as the path flow estimator for estimating O-D trip tables from traffic counts (Bell, 1998), microscopic traffic simulation (e.g., AIMSUM), and network design problems (Yin et al., 2009). The popularity is due to its analytical closed-form probability expression, relatively low calibration effort, and sound rational behavior consistent with random utility theory. Zhou et al. (2012) developed equivalent mathematical formulations of the C-logit stochastic user equilibrium (SUE) assignment problem. By integrating the logit and C-logit models, the combined mode and route choice model used in the network spare capacity has a consistent modeling rationale between mode and route choices as well as an explicit consideration of route overlapping.

For simplicity, we consider two modes: road traffic and metro traffic. The multi-modal network spare capacity can be formulated as the following bi-level programming (BLP) problem:

$$\max\ \mu \tag{2-4}$$

$$\text{s.t.}\quad v_a(\mu) \le \theta_a C_a,\ \ \forall a \in A \tag{2-5}$$

$$q_{rs}^{\text{metro}}(\mu) \le \bar{q}_{rs}^{\text{metro}},\ \ \forall r \in R, s \in S \tag{2-6}$$

where A is the set of links in the road network; R and S are the sets of origins and destinations, respectively; θ_a is a parameter denoting the pre-specified LOS required on link a; C_a is the capacity of link a; $\bar{q}_{rs}^{\text{metro}}$ is the capacity of the metro line between O-D pair (r,s); $v_a(\mu)$ is the flow on link a; and $q_{rs}^{\text{metro}}(\mu)$ is the metro travel demand, which is obtained by solving the lower-level combined mode split and traffic assignment model under a given capacity multiplier μ:

$$\min Z\left(\mathbf{v}, \mathbf{q}^{\text{metro}}\right) = \sum_{a\in A}\int_0^{v_a} t_a\left(w\right)dw$$

$$+\frac{1}{\theta_1}\sum_{r\in R}\sum_{s\in S}\sum_{k\in K_{rs}} f_k^{rs}\ln f_k^{rs} + \sum_{r\in R}\sum_{s\in S}\sum_{k\in K_{rs}} f_k^{rs}CF_k^{rs} \tag{2-1}$$

$$+\sum_{r\in R}\sum_{s\in S}\int_0^{q_{rs}^{\text{metro}}}\left(\frac{1}{\theta_2}\ln\frac{w}{q_{rs}^{\text{total}}-w}+u_{rs}^{\text{metro}}-\varphi_{rs}^{\text{metro}}\right)dw$$

s.t $\quad q_{rs}^{\text{total}} = \mu\cdot q_{rs}^0,\ \forall r\in R, s\in S \quad$ (2-2)

$$\sum_{k\in K_{rs}} f_k^{rs} + q_{rs}^{\text{metro}} = q_{rs}^{\text{total}},\ \forall r\in R, s\in S \tag{2-3}$$

$$v_a = \sum_{r\in R}\sum_{s\in S}\sum_{k\in K_{rs}} f_k^{rs}\delta_{ak}^{rs},\ \forall a\in A \tag{2-10}$$

$$f_k^{rs}\geq 0,\ \forall k\in K_{rs}, r\in R, s\in S \tag{2-11}$$

$$0 < q_{rs}^{\text{metro}} \leq q_{rs}^{\text{total}},\ \forall r\in R, s\in S \tag{2-12}$$

where t_a is the travel time on link *a* in the road network; f_k^{rs} is the flow on route *k* between O-D pair (*r*,*s*); CF_k^{rs} is a commonality factor (CF) of route *k* between O-D pair (*r*,*s*); θ_1 and θ_2 are parameters associated with route choice and mode choice; q_{rs}^{total} and q_{rs}^{metro} are the total travel demand and metro travel demand of O-D pair (*r*,*s*) corresponding to the network capacity; q_{rs}^0 is the *current* total travel demand of O-D pair (*r*,*s*); u_{rs}^{metro} is the fixed travel cost of metro between O-D pair (*r*,*s*); $\varphi_{rs}^{\text{metro}}$ is the exogenous attractiveness of metro between O-D pair (*r*,*s*); δ_{ak}^{rs} is the link-route incidence indicator: $\delta_{ak}^{rs}=1$ if link *a* is on route *k* between O-D pair (*r*,*s*), $\delta_{ak}^{rs}=0$ otherwise; π_{rs} is the Lagrangian multiplier associated with Eq. (2-9). As to the CF, Cascetta et al. (1996) proposed several functional forms, and a typical form is as follows:

$$CF_k^{rs} = \beta\ln\sum_{l\in K_{rs}}\left(\frac{L_{kl}}{\sqrt{L_k}\sqrt{L_l}}\right)^{\gamma},\ \forall k\in K_{rs}, r\in R, s\in S \tag{2-13}$$

where L_{kl} is the length of links common to routes *k* and *l*, L_k and L_l are the overall lengths of routes *k* and *l*, respectively, and β and γ are two parameters. If β is equal to zero, the C-logit model collapses to the traditional logit model.

In the above formulation, the objective function in Eq. (2-4) is to maximize the multiplier μ. In essence, it is meant to maximize the throughput of the multi-modal network, i.e., $\sum_{rs} q_{rs}^{\text{total}} = \mu\cdot\sum_{rs} q_{rs}^0$; Eq. (2-5) is the road link LOS constraint or capacity constraint; Eq. (2-6) is the metro line capacity constraint; Eq. (2-8) links the current O-D demand and the 'future' O-D demand corresponding to the network capacity;

Eq. (2-9) is the demand conservation constraint; Eq. (2-10) is a definitional constraint that sums up all route flows that pass through a given link; and Eqs. (2-11) and (2-12) are non-negativity constraints on route flows and metro demands. By deriving the first-order optimality conditions, we have the following C-logit model for route choice and binary logit model for mode choice, respectively.

$$P_k^{rs} = \frac{\exp\left(-\theta_1\left(c_k^{rs} + CF_k^{rs}\right)\right)}{\sum_{l \in K_{rs}} \exp\left(-\theta_1\left(c_l^{rs} + CF_l^{rs}\right)\right)}, \ \forall k \in K_{rs}, r \in R, s \in S \tag{2-14}$$

$$\frac{q_{rs}^{\text{metro}}}{q_{rs}^{\text{total}}} = \frac{1}{1 + \exp\left(-\theta_2\left(\pi_{rs} - u_{rs}^{\text{metro}} + \varphi_{rs}^{\text{metro}}\right)\right)}, \ \forall r \in R, s \in S \tag{2-15}$$

From Eq. (2-15), a large π_{rs} (i.e., road traffic O-D cost), a small u_{rs}^{metro} (i.e., metro traffic O-D cost), or a large $\varphi_{rs}^{\text{metro}}$ (i.e., metro attractiveness) corresponds to a large choice proportion of metro traffic.

Remark 2: Santos et al. (2010) developed the following weighted link spare capacity measure to quantify the network-wide spare capacity:

$$\sum_{a \in A}\left(C_a - v_a\right)^{\alpha} v_a L_a \Big/ \sum_{a \in A} v_a L_a \tag{2-15}$$

where L_a is the length of link a; α is a weighting parameter. When α is larger than 1.0, the spare capacities are large but concentrated on a small number of links; otherwise, the spare capacities are relatively small but more dispersed across the network. Note that the denominator is the total vehicle miles traveled. Thus, this measure is the aggregation of *link* spare capacity (i.e., $C_a - v_a$) weighted by the relative proportion of vehicle miles traveled on this link. This weighing scheme implies that we pay more attention to the spare capacity on long and heavy-flow links. This measure is simple and easy to calculate. However, it only serves as a *proxy* or a localized approximation of the network-wide spare capacity. In contrast, the network spare capacity measure adopted in this report is an optimization-based approach that can explicitly determine the maximum throughput to address the question, "How much additional demand can this multi-modal network accommodate?" This desirable feature enables planners to have a systematic assessment of multi-modal network spare capacity.

3. COMPUTATIONAL METHODS FOR EVALUATING NETWORK REDUNDANCY

This section provides the computational methods for evaluating the two network redundancy measures.

3.1 Evaluating route diversity

Meng et al. (2005) developed a combinatorial algorithm with polynomial-time complexity for counting the number of efficient routes between an O-D pair. This algorithm consists of two parts: 1) constructing a sub-network for each origin r, $G_r=(N_r, A_r)$, and 2) counting the number of efficient routes from origin r to all nodes in the sub-network $G_r=(N_r, A_r)$. The sub-network $G_r=(N_r, A_r)$ is a connected and acyclic network. The concept of *efficient routes* is used in the sub-network construction. In other words, the sub-network only includes the links that are on the efficient routes from this origin. We also modify Meng et al. (2005) to explicitly consider the requirement of *not-too-long routes*. The procedure of constructing the sub-network $G_r=(N_r, A_r)$ is as follows.

Constructing the sub-network G_r=(N_r, A_r)
For each origin r,
  Perform a shortest route algorithm to find the minimum cost from origin r to all nodes, $l_r(n)$, $n \neq r$
  For all nodes $n \neq r$
    If ($l_r(n)=\infty$) $N_r=N_r \backslash \{n\}$
  For all links a
    If ($l_r(\text{tail}_a) \geq l_r(\text{head}_a)$) or ($\left(1+\tau_r^a\right)\left(l_r\left(\text{head}_a\right)-l_r\left(\text{tail}_a\right)\right)<l_a$) $A_r=A_r \backslash \{a\}$

Note that the last if-then condition is to ensure that all links in the sub-network are in an efficient route and also in an effective route with an acceptable elongation ratio relative to the shortest route (i.e., reasonable with respect to origin r).

Counting the number of efficient routes from origin r to all nodes in the sub-network is essentially based on the node adjacent matrix operation. In the following, we present the procedure for counting the different efficient routes for each origin r. For the theoretical proof, please refer to Meng et al. (2005).

Counting the number of efficient routes from origin r to all nodes
Step 1 Initialization:
  u=0($|N_r|$, $|N_r|$)
  For all links $a \in A_r$
    $u(\text{tail}_a, \text{head}_a)=1$
Step 2 Matrix Operations:
  For all nodes $j \in N_r$
    For all nodes $m \in N_r \backslash j$
      For all nodes $n \in N_r \backslash j \backslash m$
        $u(m, n) := u(m, n) + u(m, j) \times u(j, n)$

Based on the number of efficient routes counted above, we can further evaluate the number of efficient routes using a particular link:

$$N_a^{rs} = u\left(r, \text{tail}_a\right) \times u\left(\text{head}_a, s\right) \tag{3-1}$$

where N_a^{rs} is the number of efficient routes between O-D pair (r,s) using link a; $u\left(r, \text{tail}_a\right)$ and $u\left(\text{head}_a, s\right)$ are the number of efficient routes between node pair (r, tail_a) and between node pair (head_a, s), respectively. If N_a^{rs} is equal to $u(r, s)$, then all efficient routes connecting O-D pair (r, s) need to traverse link a.

Furthermore, we can generate the efficient path set using Eq. (3-1) and these generated paths include more useful information for evaluating route diversity:

Counting the number of efficient routes using a link from origin *r* to destination *s* (e.g., how many path pass on a link) and then path generation as *u*(*r, s*)

Step 1 Initialization:

N_a^{rs}=0; $\bar{A}_{rs} = A_r$

For all links $a \in A_r$

If ($\text{tail}_a = r$) $\quad N_a^{rs} = u(\text{head}_a, s)$

Else If ($\text{head}_a = s$) $\quad N_a^{rs} = u(r, \text{tail}_a)$

ELSE $\quad N_a^{rs} = u\left(r, \text{tail}_a\right) \times u\left(\text{head}_a, s\right)$

If (N_a^{rs} =*0*) $\quad \bar{A}_{rs} = \bar{A}_{rs} \setminus \{a\}$

Step 2 Path Generation

$\bar{c}_a^{rs} = N_a^{rs},\ a \in \bar{A}_{rs}$

For n=1 to $u(r, s)$

Find shortest path k_n (r,s,$\bar{c}_a^{rs}$)

If $a \in k_n$ $\quad \bar{c}_a^{rs} = \bar{c}_a^{rs} - 1$

If ($\bar{c}_a^{rs} = 0$) $\bar{A}_{rs} = \bar{A}_{rs} \setminus \{a\}$

3.2 Evaluating Multi-Modal Network Spare capacity

The multi-modal network spare capacity model is a bi-level programming (BLP) problem. Solving this BLP problem is not a trivial task because evaluating the upper-level objective function (i.e., multiplier μ) requires solving the lower-level subprogram and also considering the capacity constraints in the upper-level subprogram. The main challenge lies in the implicit and nonlinear functions of link flow and metro demand with respect to the multiplier μ in Eqs. (2-5) and (2-6). Hence, despite having a simple linear objective function, the upper-level programming has a nonlinear and implicitly defined constraint set. To handle this issue, we can use the first-order Taylor expansion to linearly approximate the implicit link flow function $v_a\left(\mu\right)$ and metro demand function $q_{rs}^{\text{metro}}(\mu)$ at the current point $\mu^{(n)}$.

$$v_a(\mu) \approx v_a\left(\mu^{(n)}\right) + \nabla_\mu v_a\left(\mu^{(n)}\right) \cdot \left(\mu - \mu^{(n)}\right), \ \forall a \in A \tag{3-2}$$

$$q_{rs}^{\text{metro}}(\mu) \approx q_{rs}^{\text{metro}}\left(\mu^{(n)}\right) + \nabla_\mu q_{rs}^{\text{metro}}\left(\mu^{(n)}\right) \cdot \left(\mu - \mu^{(n)}\right), \ \forall r \in R, s \in S \tag{3-3}$$

where $v_a\left(\mu^{(n)}\right)$ and $q_{rs}^{\text{metro}}\left(\mu^{(n)}\right)$ are the link flow and metro demand under multiplier $\mu^{(n)}$, which can be obtained by solving the lower-level programming; $\nabla_\mu v_a\left(\mu^{(n)}\right)$ and $\nabla_\mu q_{rs}^{\text{metro}}\left(\mu^{(n)}\right)$ are the derivatives of link flow and metro demand with respect to multiplier μ, which can be obtained from the sensitivity analysis method. For our case, the logit-based probability expression for both mode and route choice dimensions ensures that the solution to the lower-level programming is unique. Hence, the standard sensitivity analysis method for the nonlinear programming problem can be used directly to derive the sensitivity information. Interested readers may refer to Yang and Chen (2009) for the detailed derivation. With the above linear approximations, the nonlinear and implicitly defined constraints in Eqs. (2-5) and (2-6) can be approximated as

$$v_a\left(\mu^{(n)}\right) + \nabla_\mu v_a\left(\mu^{(n)}\right) \cdot \left(\mu - \mu^{(n)}\right) \le \theta_a C_a, \ \forall a \in A \tag{3-4}$$

$$q_{rs}^{\text{metro}}\left(\mu^{(n)}\right) + \nabla_\mu q_{rs}^{\text{metro}}\left(\mu^{(n)}\right) \cdot \left(\mu - \mu^{(n)}\right) \le \bar{q}_{rs}^{\text{metro}}, \ \forall r \in R, s \in S \tag{3-5}$$

Note that Eqs. (3-4) and (3-5) are linear inequalities with a single solution variable μ. Hence, the upper-level programming becomes a linear programming with a single continuous variable, which is readily solvable. The solution to the above approximated linear programming generates a new solution point $\mu^{(n+1)}$, which will be iteratively used to construct a new linear approximation of Eqs. **Error! Reference source not found.-Error! Reference source not found.**. Essentially, we solve a sequence of linear approximations to the upper-level nonlinear problem.

Below we present the sensitivity analysis-based algorithm for solving the bi-level programming formulated multi-modal network spare capacity.

Estimating multi-modal network spare capacity

Step 1: Determine an appropriate initial value $\mu^{(0)}$, and set n=0.

Step 2: Solve the lower-level combined modal split and traffic assignment model based on $\mu^{(n)}$ and obtain the link flow pattern $\mathbf{v}(\mu^{(n)})$ and metro demand pattern $\mathbf{q}^{\text{metro}}(\mu^{(n)})$.

Step 3: Calculate the derivatives $\nabla_\mu v_a\left(\mu^{(n)}\right)$ and $\nabla_\mu q_{rs}^{\text{metro}}\left(\mu^{(n)}\right)$ using the sensitivity analysis method for the logit-based combined modal split and traffic assignment problem.

Step 4: Formulate a linear approximation of Eqs. (2-5) and (2-6) using the derivative information, and solve the resultant linear programming to obtain a new multiplier $\mu^{(n+1)}$.

Step 5: If $\left|\mu^{(n+1)} - \mu^{(n)}\right| \le \varepsilon$, then terminate, where ε is a predetermined tolerance error; otherwise, let n:=n+1, and go to Step 2.

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4. NUMERICAL EXAMPLES

This section provides numerical examples to demonstrate the desirable features of the two redundancy measures and the applicability of the evaluation methodology.

4.1 Example 1: Simple Network

Example 1 uses a simple network, shown in Figure 4.1, to demonstrate the features of the proposed network redundancy measures. This network has six nodes, seven links, two origins, two destinations, and four O-D pairs. The travel demand of O-D pairs (1, 3), (1, 4), (2, 3), and (2, 4) are 40, 10, 10, and 50, respectively. We use the standard bureau of public road (BPR)-type road link performance function:

$$t_a(v_a) = t_a^0\left[1 + 0.15(v_a/C_a)^4\right] \tag{5-1}$$

where t_a^0 is the free-flow travel time on link *a*. The free-flow travel time and capacity of the seven road links are also shown in Figure 4.1.

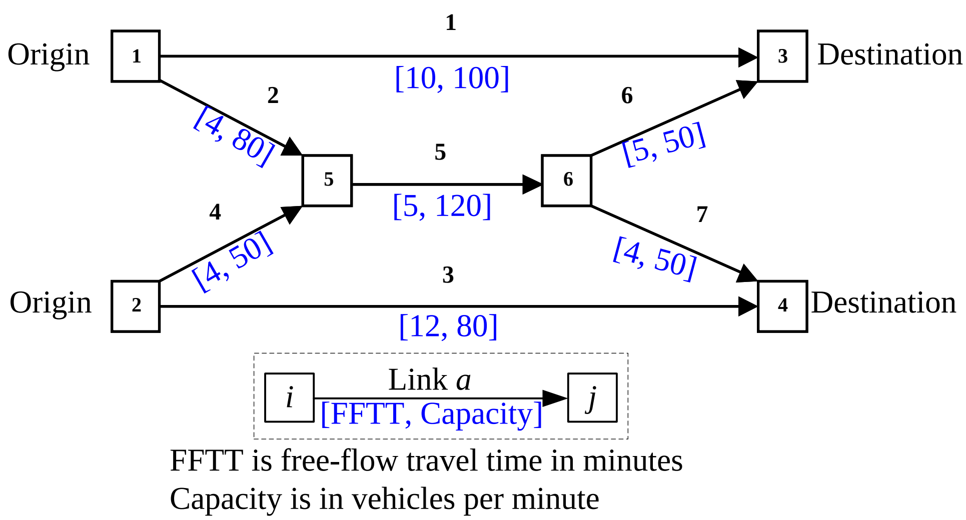

Figure 4.1 Network in Example 1

Table 4.1 A set of scenarios for the small network

Scenario	Description
0	The current road network (base case)
1	Construct a new road from node 1 to node 2 (t_a^0=4, C_a=80)
2	Expand the capacity of link 5 by 50%
3	Expand the capacity of link 3 by 50%
4	Construct a new road from node 1 to node 6 (t_a^0=6, C_a=80)
5	Construct a new road from node 2 to node 6 (t_a^0=6, C_a=80)
6	Construct a metro line from origin 1 to destination 3
7	Construct a metro line from origin 2 to destination 4

4.1.1 General relationship of the two dimensions

We first examine how travel alternative diversity and network spare capacity complement each other for network redundancy characterization. The number of travel alternatives (e.g., routes and modes) of the four O-D pairs and the network capacity multiplier under the above eight scenarios are shown in Table 4.2. By comparing Scenario 1 with Scenario 0 (base case), constructing a new road from node 1 to node 2 will increase the degree of connections of O-D pairs (1, 3) and (1, 4) from 2 to 3 and from 1 to 3, respectively. However, the network spare capacity multiplier is the same as that in Scenario 0. On the other hand, the comparison among Scenario 2, Scenario 3, and Scenario 0 indicates that expanding these link capacities can only change (decrease in Scenario 2 and increase in Scenario 3) the network spare capacity while keeping the degree of connections intact. Scenarios 0, 1, 4, and 6 have similar or even identical network spare capacity values, whereas the degrees of connections of O-D pairs (1, 3) and (1, 4) are obviously different. In addition, Scenario 4 and Scenario 5 change both dimensions simultaneously. However, they increase the degree of connections but decrease the network spare capacity. Adding a new road may not always increase the network-wide spare capacity (to be explained later). Similar phenomenon also occurs in Scenario 6 and Scenario 7 of constructing a metro line for the two O-D pairs with large travel demands. It seems that there is a trade-off between travel alternative diversity and network spare capacity. Using either travel alternative diversity or network spare capacity solely, may not be able to capture the full picture of network redundancy under different network reconfiguration or enhancement schemes. However, they can complement each other to provide a two-dimensional transportation network redundancy characterization. This also shows the importance of "integrating" the two dimensions in order to avoid a biased network redundancy assessment. Therefore, we need to optimize them simultaneously (as a bi-objective problem) in order to design an optimal redundant transportation network.

Table 4.2 Network redundancy performances under different scenarios

Scenario	Number of alternatives (modes + routes)				Network spare capacity (multiplier)
	O-D (1,3)	O-D (1,4)	O-D (2,3)	O-D (2,4)	
0	2	1	1	2	2.16
1	***3***	***3***	1	2	***2.16***
2	2	1	1	2	2.15 (↓)
3	2	1	1	2	2.51 (↑)
4	**3**	**2**	1	2	2.15 (↓)
5	2	1	**2**	**3**	0.93 (↓)
6	3	1	1	2	2.16
7	2	1	1	3	2.51 (↑)

4.1.2 Travel Alternative Diversity

Secondly, we examine the travel alternative diversity dimension. Note that the basic definition of alternative (mode and route) diversity is at an O-D pair level measuring the degree of connections for a specific O-D pair. However, we can aggregate it to different spatial levels according to planners' different evaluation purposes. Below, we use the corresponding O-D demands as the weights to aggregate the O-D pair level to zonal level and network level, as seen in Table 4.3. Scenario 4 and Scenario 5 have a symmetric degree of connections at the O-D pair level. However, the degrees of connections at the zonal and network levels are different, as indicated in Table 4.3. Particularly, the number of routes to destination 3 and destination 4 are the same (i.e., four) in both scenarios, whereas the aggregated degrees of connections to these two destinations are different. The reason is that the above aggregation explicitly considers the effect of travel demand on route diversity. Typically, O-D pairs with large travel demands need more available routes to disperse the travel demands. In addition, constructing a new road from node 1 to node 6 in Scenario 4 (from node 2 to node 6 in Scenario 5) is quite beneficial for the connections of origin 1 and destination 3 (origin 2 and destination 4). Similar changes also occur in Scenarios 6 and 7 when constructing a new metro line from origin 1 to destination 3 and from origin 2 to destination 4. Travelers are the direct users of this dimension. Particularly, evacuees from a residential zone are eager to know how many choices (routes and/or modes) are available for getting to a particular shelter. In addition, the network planners could use the above aggregation for improving the route diversity of important zones.

Table 4.3 Travel alternative diversity under different scenarios

Scenario	O-D (1,3)	O-D (1,4)	O-D (2,3)	O-D (2,4)	O-1	O-2	D-3	D-4	Network
0/2/3	2	1	1	2	1.80	1.83	1.80	1.83	1.82
1	3	3	1	2	3.00	1.83	2.60	2.17	2.36
4	3	2	1	2	2.80	1.83	2.60	2.00	2.27
5	2	1	2	3	1.80	2.83	2.00	2.67	2.36
6	3	1	1	2	2.60	1.83	2.60	1.83	2.18
7	2	1	1	3	1.80	2.67	1.80	2.67	2.27

4.1.3 Network Spare Capacity

Thirdly, we explain why the network spare capacity has different changes under the above scenarios. Recall that the network spare capacity model determines the maximum throughput of the network while considering congestion effect, route choice behavior (via C-logit model with route overlapping consideration) and mode choice behavior (via logit model). Also, the link capacity constraint is a main barrier of preventing the network capacity increase. Table 4.4 shows the binding links (i.e., link flow equals capacity) in network capacity evaluation under the above scenarios.

- *Scenario 1*: In the base scenario, links 3, 4, and 7 are the binding links. These three links remain active in Scenario 1 despite a new road being added from node 1 to node 2. Accordingly, the network spare capacity cannot be further increased. This is because even though it increases the degree of connections of origin 1, this new road is seldom used by travelers due to the large route travel cost.
- *Scenarios 2 and 3*: These two scenarios expand the capacity of link 5 and link 3, respectively. Link 5 seems to be a critical link from a pure network topology perspective. However, it is not a critical link in terms of congestion, as shown in Table 4.4. Expanding link 5 in Scenario 2 may divert some travelers from link 3 to links 4-5-7. This diversion will increase the burden on the binding links 4 and 7, leading to a slight decrease of network capacity. Instead, link 3 is actually the most critical binding link in this network (to be shown further in Figure 4.2). Scenario 3 considers all three critical binding links by expanding link 3. Hence, it has a substantial increase of network spare capacity.
- *Scenarios 4 and 5*: From a pure network topology standpoint, these two scenarios have a symmetric effect on network redundancy. This is witnessed by the improvement of route diversity. However, they have significantly different network spare capacity values. In Scenario 4, constructing a new road from node 1 to node 6 will divert flows from links 2 and 5 to the new link. However, the remaining binding link 7 blocks the possible throughput increase of O-D pair (1, 4) (i.e., link 2-5-7). In Scenario 5, constructing a new road from node 2 to node 6 has made links 3 and 4 non-binding. However, the traffic diversion from link 3 and links 4-5-7 to the new road will further overwhelm the binding link 7, making the network overloaded by 7% of the existing O-D demand.

- *Scenarios 6 and 7*: In Scenario 6, the new metro line from origin 1 to destination 3 does not relax the three binding links 3, 4, and 7 since it mainly diverts demands of O-D pair (1, 3) from road to metro. Accordingly, the network spare capacity remains unchanged. However, this scenario is still meaningful since it creates an alternative mode besides the road traffic mode, especially when the road network encounters a significant disruption (e.g., bridge collapse). In Scenario 7, the construction of a new metro line from origin 2 to destination 4 increases both travel alternative diversity and network spare capacity. It diverts demands of O-D pair (2, 4) from road to metro, relaxing all three binding links.

Table 4.4 Binding links in network capacity evaluation under different scenarios

Scenario	Binding Links							
	1	2	3	4	5	6	7	8
0	×	×	√	√	×	×	√	×
1	×	×	√	√	×	×	√	×
2	×	×	×	√	×	×	√	×
3	√	×	×	×	×	×	×	×
4	×	×	√	√	×	×	√	×
5	×	×	×	×	×	×	√	×
6	×	×	√	√	×	×	√	×
7	√	×	×	×	×	×	×	×

Finally, we continue to examine the role of the three congested critical links (i.e., links 3, 4, and 7) in the network spare capacity. These congested critical links are associated with the network-wide capacity rather than only their individual congestion since they are vital for network capacity improvement. Figure 4.2 shows the network spare capacity under all possible combinations of their link capacity enhancements. One can observe that link 3 is the most critical link for network spare capacity improvement. All cases with capacity enhancement on link 3 (i.e., cases 2, 5, 6, and 8) have the largest network capacity multiplier value. After expanding link 3, the original binding capacity constraints on the three critical links become inactive due to the flow shift from links 4-5-7 to link 3, and subsequently the network can thus absorb more demands. However, if we only expand link 4 as in case 3 (or link 7 in case 4), flows will be diverted from link 3 to links 4-5-7. This flow shift will increase the burden on binding link 7 (or 4), resulting in a decrease of network spare capacity. Hence, ranking the congested critical links appropriately enables planners to prioritize the candidate capacity enhancement projects more cost effectively for improving network spare capacity.

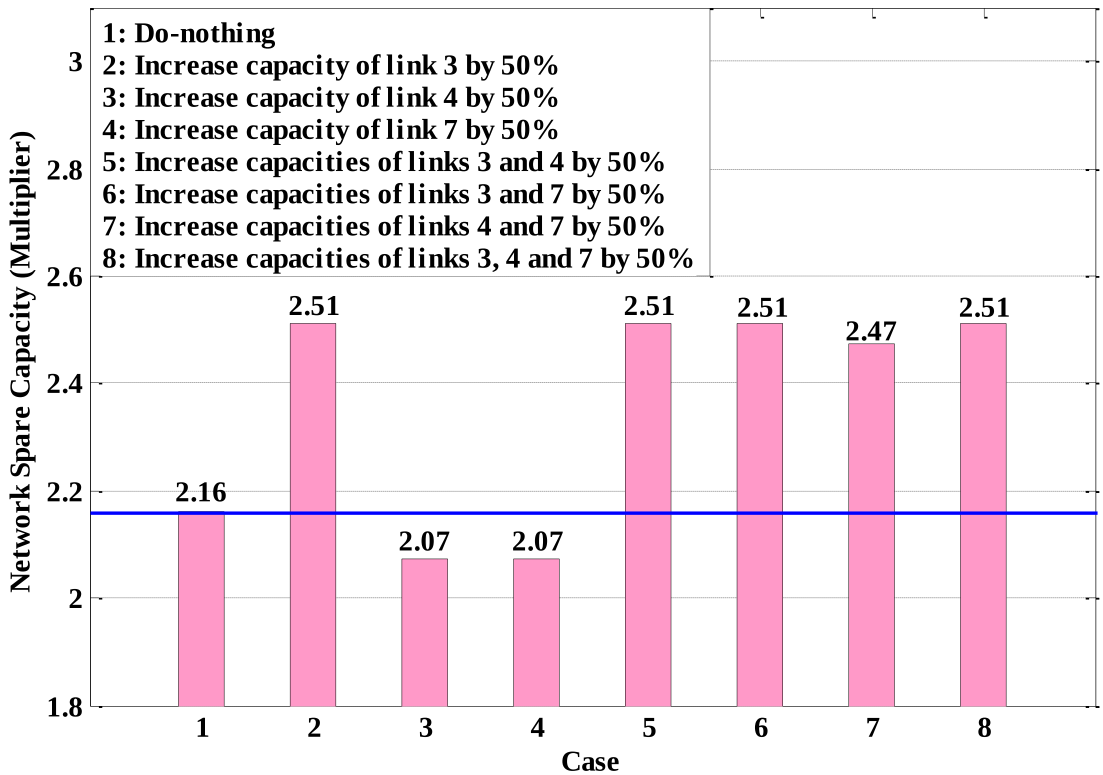

Figure 4.2 Network spare capacities under different capacity enhancement schemes

4.2 Example 2: Winnipeg Network

In this section, we conduct a case study using the Winnipeg network in Manitoba, Canada, to demonstrate the applicability of the computational methods. The Winnipeg network, shown in Figure 4.3, consists of 154 zones, 1,067 nodes, 2,535 links, and 4,345 O-D pairs. The network structure, O-D trip table, and link performance parameters are from the Emme/2 software (INRO Consultants, 1999). Due to lack of metro data in the Winnipeg network, we consider only the road traffic network. Other parameters are set as follows: θ_1=1.2 (route choice), $\beta = 1$ and $\gamma = 1$ (commonality factor), and $\tau_r^a = 1.4, \forall a \in A, r \in R$ (elongation ratio in not-too-long routes). The computational methods presented in Section 3 are performed to evaluate the travel alternative diversity and network spare capacity.

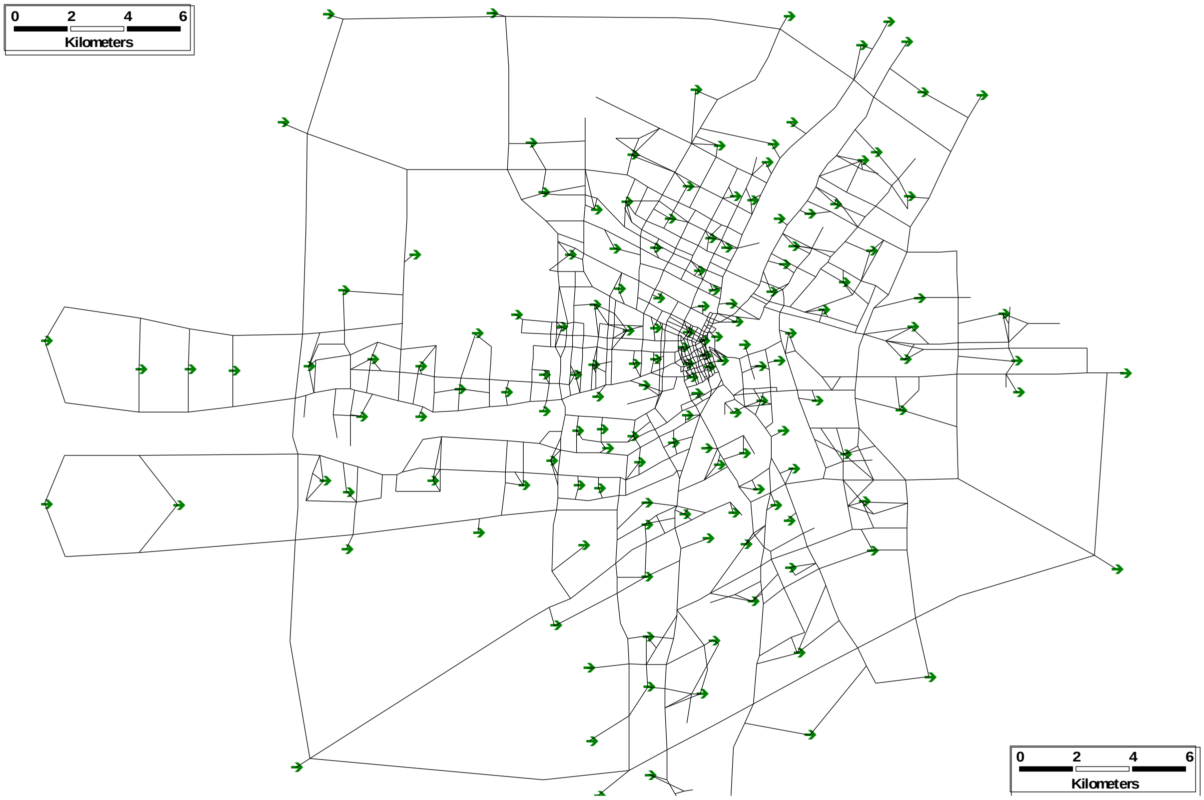

Figure 4.3 Winnipeg network

Travel Alternative Diversity: Recall that we define an effective route as not only an efficient route but also a not-too-long route. From Figure 4.4, we can see that all O-D pairs have at least one effective route and, at most, 634 effective routes. The average number of effective routes per O-D pair is 11.63 and the median is four for all O-D pairs. Also, 62.55% and 78.18% of all O-D pairs are connected by, at most, five and 10 effective routes, respectively. As a comparison, Figure 4.5 shows the number of efficient routes (may be too-long routes relative to the shortest route) for all O-D pairs. One can see that ignoring the requirement of not-too-long routes will significantly overestimate the degree of valid connections. Behaviorally, a shorter detoured route with an acceptable travel cost is more likely to be considered by travelers as a reasonable substitution when the primary or secondary route is not available.

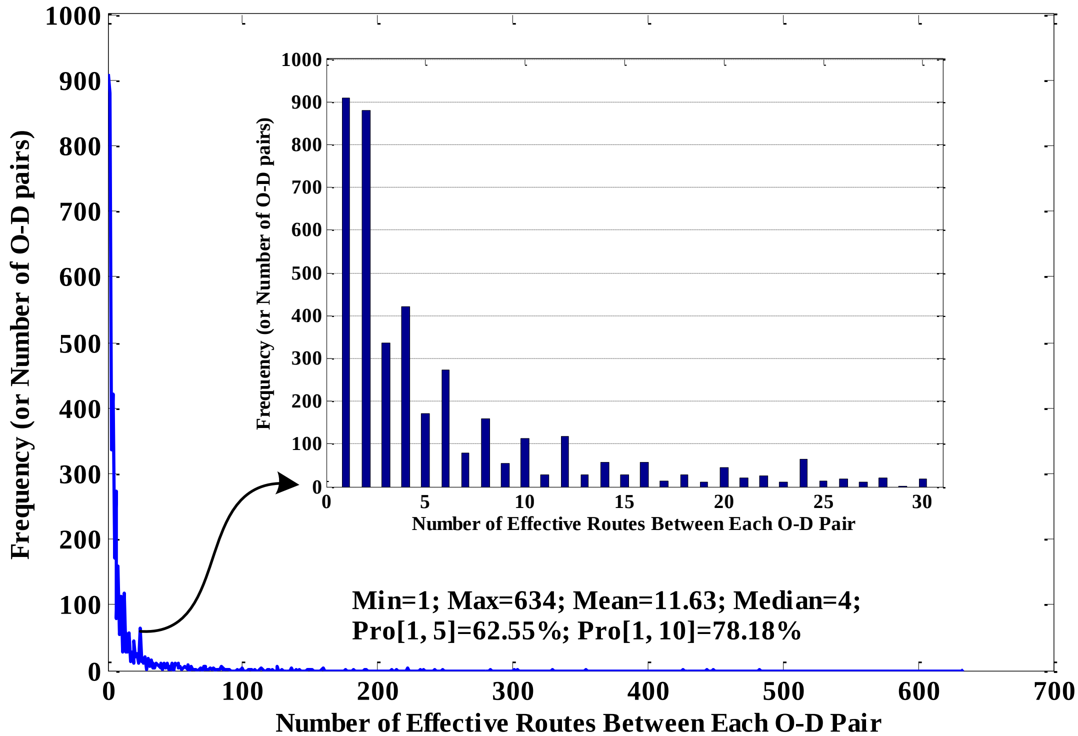

Figure 4.4 Number of effective routes (efficient and not-too-long) in the Winnipeg network

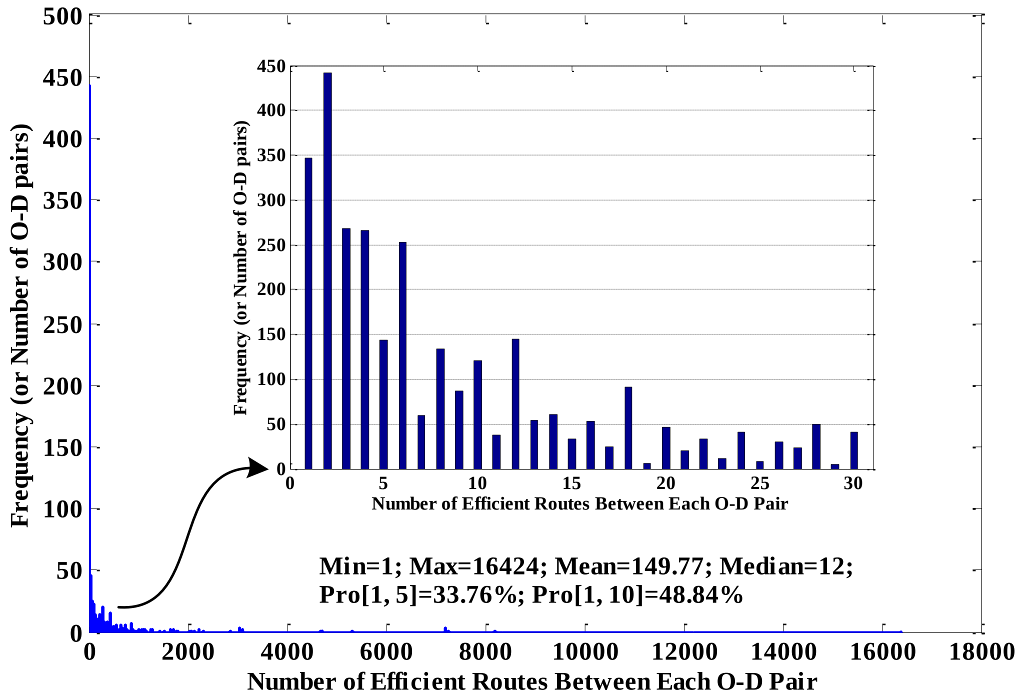

Figure 4.5 Number of efficient routes in the Winnipeg network

Network Spare Capacity: As mentioned before, the link capacity constraint is a main barrier of preventing the network capacity improvement. Figure 4.6 shows the number of links with V/C>1 under each value of multiplier μ. One can see then at the current demand pattern, the flows of 206 links (i.e., 8% of 2,535 links) exceed their capacities. With the decrease of multiplier μ, the number of links with V/C>1 are reduced quickly. When multiplier μ is equal to 0.37, all links can satisfy the link capacity constraints. This network appears to have a lot of room for improving network capacity, at least in this particular scenario. In order to accommodate the current travel demands, planners should improve the network by expanding existing roads, constructing new roads, and/or alternative travel modes, or both. Similar to Example 1, congested critical links associated with network capacity should be identified in the planning process.

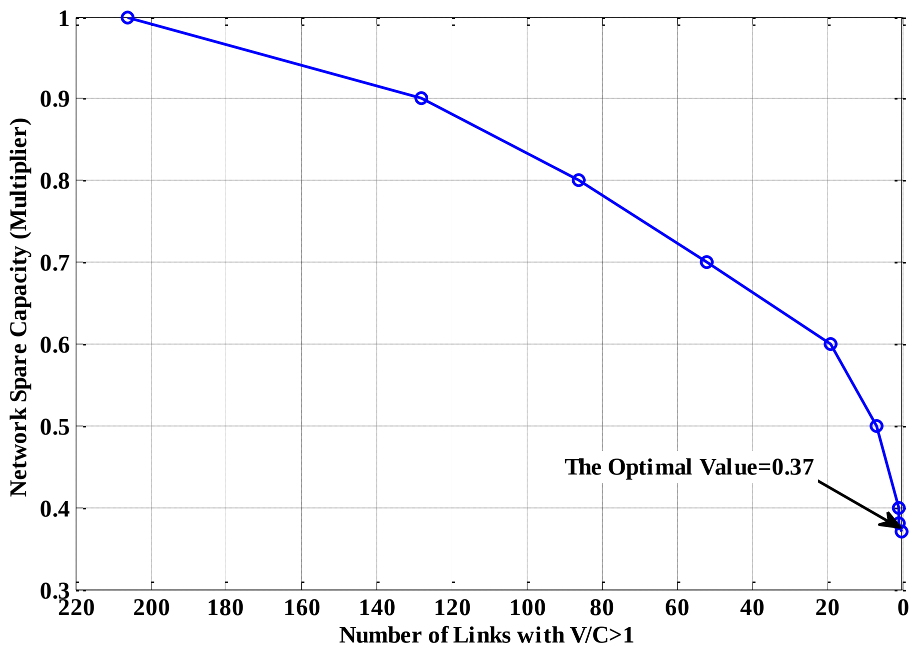

Figure 4.6 Network spare capacity of the Winnipeg network

5. CONCLUDING REMARKS

This project developed network-based measures and computational methods to systematically characterize transportation network redundancy, i.e., travel alternative diversity and network spare capacity. The travel alternative diversity dimension evaluates the existence of multiple modes and effective routes available for travelers or the degree of effective connections between an O-D pair. The network spare capacity dimension quantifies the network-wide residual capacity with an explicit consideration of congestion effect and travelers' route and mode choice behaviors. To implement the two measures in practice, a formal methodology was provided to evaluate the network redundancy.

Two set of numerical examples were provided. Example 1 in the simple network demonstrated the necessity of having the two dimensions together for systematically characterizing transportation network redundancy. Example 2 in the Winnipeg network demonstrated the applicability of the computational methods as well as the importance of considering the requirement of not-too-long routes in the travel alternative diversity measure. The analysis results revealed that the two measures have different characterizations on network redundancy from different perspectives. Using either dimension solely may not be able to capture the full picture of network redundancy under different network reconfiguration or enhancement schemes. They can complement each other by providing meaningful information to travelers as well as assist planners to enhance network redundancy in their infrastructure investment decisions. Adding a new road/metro line or enhancing existing links may not always increase the network capacity. A topologically critical link may not necessarily be a binding link in terms of improving network capacity. A well designed future network with alternative travel modes could significantly increase the network spare capacity to accommodate a substantial demand increase. Multi-modal network redundancy improvement generally involves high capital and long-term investments, and cannot be reversed easily. Therefore, a tailored multi-modal network spare capacity estimation is particularly crucial in the pre-disaster network planning in order to avoid biased and ineffective investment decisions. Particularly, we need to explicitly consider the potential adjustment of travelers' choice behaviors.

For future research, we will explore different applications of the redundancy assessment methodology. An interesting application is to assess network redundancy under various potential bridge disruptions. This analysis is particularly insightful in identifying the critical bridges in the network and prioritizing bridge retrofits for enhancing network redundancy. Also, we will try to integrate the two dimensions to facilitate the redundancy comparison among different cities/regions. In this report, we considered route overlapping in the C-logit route choice model. Mode similarity could also be considered by a nested logit model (Kitthamkesorn et al., 2013). In addition, network redundancy improvement belongs to the mixed network design problem, which involves the continuous capacity expansion for improving network spare capacity and also the discrete alternative addition for improving both dimensions. We will investigate the mathematical modeling and solution algorithm of this problem.

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