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A R T I C L E I N F O

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A B S T R A C T

Transport network criticality analyses aim at identifying important segments in a transport network. Such studies are often based on the utilitarian principle, where the criticality of a segment is assessed based on its contribution to the aggregate performance of the transport system. To allow for the use of alternative moral principles, I systematically operationalize concepts from the transport equity literature into an equity-based criticality analysis framework. There are two main ideas in this framework: calculation of equity-weighted transport demand based on distributive moral principles and adaptation of an equity-weighted user equilibrium assignment algorithm. Using the Bangladesh freight transport network as a case study, I show that different sets of transport segments emerge as being critical when different moral principles are used. The use of some pairs of moral principles, for example global equalization and proportionality, even produces a negative ranking correlation. This implies that links which are considered to be critical based on one principle are not at all critical based on the other one. Selection of a moral principle, either explicitly or implicitly, is an inevitable step in transport network criticality analysis. Hence, it is advised to use multiple moral principles or to make a deliberative selection of a moral principle, as considering alternative moral principles in a criticality analysis could expose previously overlooked transport segments.

1. Introduction

Transport network criticality analysis aims to calculate the importance of each segment in a transport network (Almotahari and Yazici, 2020; Jafino et al., 2020; Jenelius et al., 2006). This results in a rank-ordering of each segment vis-à-vis all other segments based on its contribution to the performance of the transport system. The results are often used to prioritize interventions, including strategic disinvestment of road infrastructure (Novak et al., 2020), climate resilient transport interventions (Demirel et al., 2015; Espinet et al., 2016; Ortega et al., 2020; Papilloud et al., 2020), (post-)disaster transport infrastructure reparation (Aydin et al., 2019; Merschman et al., 2020; Nelson et al., 2019; Zhu et al., 2020), and bicycle lane improvement (Lowry et al., 2016).

Transport network criticality analysis complements other network-based transport studies such as societal vulnerability analysis (identification of transport users' exposure to disruptions) and robustness analysis (performance comparison of several transport networks). The main distinction between criticality analysis with other network-based analysis lies on the object of the study for which indicators are calculated. In criticality analysis, the object of analysis is the transport segments (how critical is a transport segment?) (Jafino et al., 2020). On the contrary, societal vulnerability analysis focuses on the transport users (how much disruptions would transport users experience?) (Jenelius and Mattsson, 2015) while robustness analysis focuses on the comparison of the performance of an entire transport network (which transport network is more robust?) (Sullivan et al., 2010). Other terminologies have also been used for criticality analysis, such as centrality (Cats and Krishnakumari, 2020), importance (Baroud et al., 2014; Qi et al., 2015), and link-level or technological vulnerability analysis (De Oliveira et al., 2016; Jenelius and Mattsson, 2015; Knoop et al., 2012).

The selection of metrics used to indicate the criticality of transport segments involves three conceptual dimensions (Jafino et al.,

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2020). The first dimension is the functionality of the transport service that is being accounted when calculating criticality. The functionalities can be either providing connectivity, reducing travel cost incurred by users, or improving accessibility (Lakshmanan, 2011; Velaga et al., 2012). The second dimension is the moral principles underlying the metrics. Drawing from theories of distributive justice, the most common moral principles used are utilitarianism and egalitarianism (Pereira et al., 2016; Van Wee and Roeser, 2013). The third dimension is the spatial scope at which the benefits of the transport infrastructure are observed. Some criticality metrics evaluate the contribution of transport segments to all users in the transport system, while others evaluate the contribution only to a subset of users (e.g., only to users residing in the same location with the transport segment). Any criticality metric always represents a combination of the three dimensions above. For instance, the widely used demand-weighted betweenness centrality metric evaluates the contribution of transport segments in reducing the total travel costs of all users from a utilitarian perspective.

With respect to the moral principle dimension, transport network criticality studies are often implicitly based on a utilitarian principle. Utilitarian aims to maximize the total utility of all actors. The criticality of transport segments is then assessed based on their contribution to the aggregate service level experienced by all transport users, regardless of the users' spatial, social, and economic background. Two of the most widely used criticality metrics exemplify this. The betweenness centrality metric is calculated through the assignment of transport demand on the transport network. The transport demand can be generated based on various variables, such as total population (e.g., Lowry et al., 2016; Pant et al., 2016; Yap et al., 2018) and total economic activities (de Jong et al., 2013; Halim et al., 2016; Holguín-Veras et al., 2014; Tavasszy et al., 2012). The demand is then generated for each transportation analysis zone. Likewise, interdiction criticality, another widely used metric, often uses a similar approach for generating the transport demand (Cats and Jenelius, 2016; Espinet and Rozenberg, 2018; Li et al., 2020). The use of such an aggregate transport demand symbolizes the adoption of a utilitarian principle, since the subsequent analysis that follows is based on the objective of maximizing the fulfillment of the aggregate demand, irrespective of the socioeconomic background of the people that create the demand (Martens and Hurvitz, 2011).

Decisions taken on the basis of a utilitarian moral ground could exacerbate, if not maintain, the existing inequalities (Konow, 2003; Leroux and Ponthiere, 2013; Pazner and Schmeidler, 1978). The fundamental reason behind this is because utilitarian is concerned with maximizing utility but is blind to the way in which the utility is distributed among people. The evidence of worsening inequalities due to utilitarian decisions is abundant especially in the environmental and climate change domain (Atteridge and Remling, 2018; Sayers et al., 2018; Stanton et al., 2009), while fewer but increasing evidence is present in the transport domain (Beyazit, 2015; Pereira et al., 2017; Van Wee and Geurs, 2011; Yu et al., 2016). Nevertheless, the same line of reasoning found in the climate change domain can be followed in the transport domain. In a utilitarian world, resources are allocated to transport infrastructure that is used by more users, such that they yield higher overall benefits. Less resources would then be apportioned to transport infrastructure that is less often used, such as roads that connect rural areas. Ultimately, the use of a utilitarian principle – as is the case in most cost-benefit analyses – could lead to a widening transport service inequalities (Martens, 2006).

In doing criticality analysis, it is important to consider alternative moral principles so that unintended distributional consequences can be anticipated. To this end, this paper proposes an analytical framework for an equity-based transport network criticality analysis. This analytical framework is based on the theoretical framework of horizontal equity and distributive justice in transport studies (Litman, 2002; Martens et al., 2019; Pereira et al., 2016), specifically operationalized for the context of criticality analysis. The analytical framework contains two important steps: the calculation of equity-weighted transport demand and its assignment on the transport network. For the first step, I adapt the equity weighting techniques that are common in the climate justice literature (Anthoff and Tol, 2010; Hope, 2008). This results in an equity-weighted transport demand where trips between different origin–destination pairs are given different importance, depending on the specific distributive moral principle that is being adopted as well as based on the (socio-economic) attribute of the transport users. The inequality among the transport users, measured through the users' attributes, is thus reflected and embedded at this stage. For the second step, I adapt the standard user equilibrium assignment to account for both

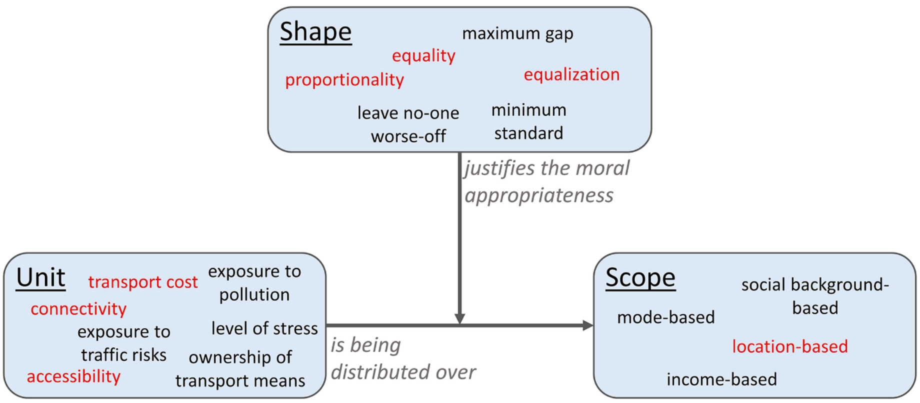

Fig. 1. Three components within the theoretical framework of distributive justice in transport studies, as well as possible elements within each component (see Martens et al. (2019) for a more detailed discussion). Elements which are applicable for transport network criticality analysis are highlighted in red. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the equity-weighted transport demand and the original transport demand. The final outcome is equity-weighted criticality scores for all transport segments in the network. These scores have the adopted moral principle and the inequalities among the transport users internally embedded in them, as they are calculated on the basis of the equity-weighted transport demand.

An implementation of this analytical framework for a Bangladesh inter-district freight transport network case study is then presented. The case study aims to understand to what extent the use of different moral principles yields distinctive criticality results. The proposed framework, however, is generic for other contexts in which criticality analysis is being used.

2. Literature review: Equity in transport planning

The field of transport equity studies has emerged in recent years to explicitly reflect on moral dilemmas in and distributive consequences of transport policies (Beyazit, 2011; Di Ciommo and Shiftan, 2017; Martens et al., 2019). Although the field began with a specific issue of lack of accessibility and transport supply provision for marginalized population (e.g., Delbosc and Currie, 2011a; Hernandez and Dávila, 2016; Lucas, 2012), it has evolved into a broader concern that might require its own sphere of justice (Martens, 2020; Vanoutrive and Cooper, 2019). A fundamental question of the field is the identification of population groups who would become 'gainers' and 'losers' from transport policies and how benefits and burdens would be distributed among the population groups. Hence, concepts within the transport equity field mainly draw from the theoretical framework of distributive justice (Konow, 2001; Pereira et al., 2016; Törnblom and Vermunt, 1999).

The application of the theoretical framework of distributive justice in transport studies requires specifying three components (see Fig. 1) (Martens et al., 2019). They are coined as the *unit, scope,* and *shape* of the distribution (Bell, 2004; Page, 2007). The *unit* of the distribution refers to the benefits and burdens that are being distributed. This could be for instance public transport availability, accessibility to points of interest, or enjoyment of travel. The *scope* of the distribution refers to the beneficiaries of the *unit.* The concern here is how a population is disaggregated into social groups, so that the distribution of the *unit* among these groups can be evaluated. There are two alternative but complementary perspectives for this: vertical equity and horizontal equity (Litman, 2002). The former concerns the distribution of *unit* among groups with different (socio-economic) background. This comprises, among others, differentiating a population based on the age, income, or other social indicators of the individuals (Bocarejo and Oviedo, 2012; Delbosc and Currie, 2011b; Foth et al., 2013). The latter concerns the distribution of *unit* among groups that are considered equal. This comprises, for example, distribution of *unit* among different municipalities or transportation analysis zones (Delmelle and Casas, 2012; Kaplan et al., 2014; Monzón et al., 2013). The horizontal equity perspective fits the nature of transport network criticality analysis, as in such an analysis the population is normally distinguished based on their location (e.g., districts, census tracks, or grid).

The *shape* of the distribution refers to the conceptually ideal distribution of benefits and burdens among the beneficiaries. This is often grounded on some moral principles. The utilitarian principle, for instance, is considered to be agnostic to the shape of the distribution; any distribution is justified as long as it maximizes the total utility. Other moral principles such as Rawlsian egalitarianism and sufficientarianism have their own maxim in justifying the righteousness of a distribution (Lucas et al., 2016; Pereira et al., 2016). Different transport-specific moral principles have been proposed depending on the type of the studies (Martens et al., 2019). The first type of study is assessing the fairness of an existing situation. Moral principles for this category include, among others, equality (a situation with perfectly equal distribution of burdens and benefits), proportionality (a situation where burdens and benefits are allocated proportionally to the size of the groups), and minimum standard (a situation where inequality is accepted as long as a minimum level of benefits are secured for each group (e.g., Martens and Bastiaanssen, 2019)). The second type of study is assessing the fairness and the distributional consequences of alternative interventions. Moral principles such as equality (an intervention should distribute equal burdens and benefits for each group) and equalization (an intervention should reduce existing disparities by making currently worse-off group better) have been proposed to be relevant for this category.

Equity considerations in transport studies could be found especially in appraisals of transport policies and interventions. Here, equity is considered as an additional criterion in project selection (Lee et al., 2017; Litman, 2007; Nahmias-Biran et al., 2017; Van Wee, 2011). Such studies focus on *a-posteriori* analysis of transport projects. They look at equity impacts due to the implementation of the projects, either through quantitative models or empirical data. Equity impacts can be measured in two complementary ways. The first way is through computing an aggregated indicator that capture the entire inequality among all transport users/groups. The use of Lorenz curve and Gini indicator is often endorsed for this, although other alternative indicators are also present (Ben-Elia and Benenson, 2019; Delbosc and Currie, 2011b; Jang et al., 2017; Klein, 2007; Welch and Mishra, 2013). The second way is by looking at the impacts of the intervention to the distribution of benefits and burdens among the social groups (Golub and Martens, 2014; Guzman and Oviedo, 2018; Karner and Golub, 2019; Kim and Sultana, 2015; Zhao and Howden-Chapman, 2010). An advantage of this second approach is that it allows for identifying social groups that become better-off and worse-off after the intervention.

Equity considerations are also gaining attraction in network-based transport planning (Behbahani et al., 2019a; France-Mensah et al., 2019; Mollanejad and Zhang, 2014; Shang et al., 2018). A distinctive characteristic here is that equity considerations are accounted *a-priori,* where equity is internally embedded during the optimization search for candidate interventions. For example, Behbahani et al. (2019b) operationalize Rawls' social justice principle into an objective function in a discrete network design problem. The Rawlsian objective function aims to maximize the total accessibility of poorer population subgroups in the study area, instead of maximizing the total accessibility of all population. This new objective function replaces the traditional travel cost minimization function in the first level objective of the bi-level optimization model. Other moral principles drawing from various theories of equity, such as utilitarian liberalism, Christianity, socialism, and deontological liberalism, have also been adopted to formulate equity-based objective functions in such network design problems (Behbahani et al., 2019a).

While equity considerations have been found in transport network design problems, their assimilation in transport network criticality analysis is still lacking. Many recent transport network criticality analysis studies still implicitly use the utilitarian principle (Balijepalli and Oppong, 2014; Dehghani et al., 2014; Du et al., 2014; Gauthier et al., 2018; Merschman et al., 2020; Ortega et al., 2020). An exceptional contribution on this topic is a study by Jenelius (2010). The study departs from the common utilitarian-based criticality analysis by using a coefficient of variation as a criticality metric. The coefficient of variation is a dimensionless metric that calculates the unevenness of the travel cost increases among travelers when a transport network component is disrupted. Unlike Behbahani et al. (2019a), however, Jenelius (2010) does not provide any reflection on the underlying moral principles that guide the selection of the criticality metric.

3. Methodology: An equity-based criticality analysis framework

The equity-based criticality analysis framework proposed in this study is a modification of a standard criticality analysis framework that uses betweenness centrality as the criticality metric (Fig. 2). The *unit* of the distribution reflected from the use of the betweenness centrality metric is transport cost experienced by users (Jafino et al., 2020). A standard criticality analysis framework basically follows the classic four-step transport modelling approach (Jafino et al., 2020; Ortuzar and Willumsen, 2011b), as illustrated on the top row of Fig. 2. This includes trip generation (calculating the generation of transport activities from each group within the *scope* of the distribution – in our case the transportation analysis zones (TAZs)), OD matrix calculation (constructing an origin–destination matrix that contains information on how many transport activities are demanded between each pair of TAZs), and trip assignment (assigning the transport demand from the OD matrix to the transport network). The network assignment resulting from the four-step transport model is taken as-is where the simulated traffic on each transport component becomes the criticality score of that component.

The equity-based criticality analysis framework adds a parallel sequence of steps as depicted on the bottom row of Fig. 2. The central idea here is assigning certain equity weights to transport activities originating from and going to each TAZ. Therefore, depending on the moral principles, each trip might not be counted equally, as the attribute of the person behind the trip affects the relative importance of that trip. Such weighting approaches have been widely used in planning for climate justice where the impacts of climate policies are weighted based on the attributes and characteristics of the subgroups that bear the impacts (Anthoff and Tol, 2010; Hope, 2008; Stanton, 2011). In the context of transport network criticality analysis, this is achieved in two steps. The first step is calculating equity weights for each TAZ based on the adopted distributive moral principle and the weighting variables (i.e., the attributes of the TAZ) for which the distribution is being observed. The second step is simply applying these equity weights on the original OD matrix which then results in an equity-weighted OD matrix. These two steps are explained in more detail in Section 3.1.

To identify appropriate moral principles to use, we have to understand which type of study transport network criticality analysis belongs to (see the discussion on the *shape* of distribution in Section 2). On the one hand, criticality analysis portrays the importance of each transport segments based on the current situation of the transport system. At the same time, it aims at providing support for transport network intervention planning. Therefore, from a theoretic point of view, moral principles from both types of studies are appropriate and can be used for an equity-based criticality analysis. In this study, the use three moral principles introduced by Martens et al. (2019) is proposed: proportionality, equality, equalization principles. The equalization principle is further delineated into global and good neighbor equalization, as suggested by the application of the similar principle in the climate justice domain (Anthoff and Tol, 2010).

The spatial distribution of the equity-weighted transport demand is perceptibly different from the spatial distribution of the original transport demand, unless the utilitarian principle is adopted. Hence, using the equity-weighted transport demand as an input to the equilibrium assignment algorithm would interfere the physical consistency of the assignment. The assignment should maintain the physical representation of the original transport demand, while only adjusting the weights of the transport activities in accordance to the selected moral principle. Therefore, an adaptation of the default equilibrium assignment is introduced in the equity trip assignment (see Fig. 2). This step is explained further in Section 3.2. The resulting equity-based assignment is then used as the equity-based criticality scores.

3.1. A procedure for transport demand equity weighting

The first step of the equity-based criticality analysis framework is the weighting of the transport activities represented by the transport demand, resulting in an equity-weighted origin–destination (OD) matrix. The weighting procedure is dependent on the

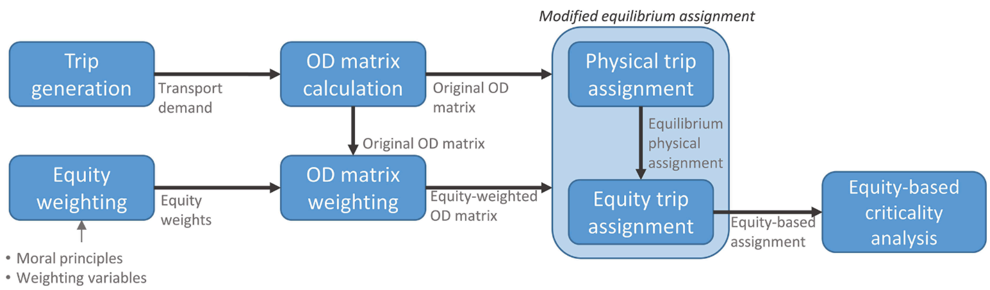

Fig. 2. Equity-based transport network criticality analysis framework.

selected moral principles. Table 1 shows the proposed transport demand weighting functions based on the operationalization of the distributive moral principles.

Each moral principle has its own maxim in justifying the appropriateness of a distribution. The proportionality principle requires that good or bad is distributed proportionally to the size or level of the social subgroups' attributes. This resembles the utilitarianism school of thought, where the main concern is maximizing the overall utility experienced by all population (Posner, 1979). As a consequence, a higher equity weight should be given to TAZs whose attribute size is larger. By default, transport demand between two TAZs is calculated based on the socioeconomic attributes of the TAZs. Therefore, the original transport demand calculation has satisfied this conception, as by default the demand between TAZ i and j is proportional to the attributes (e.g., economic activities) of the two TAZs. Hence, the original transport demand d_{ij} can be directly used as the equity-weighted transport demand d^e_{ij}.

The equality principle promotes an equal distribution of good or bad to all subgroups in a system, irrespective of the attribute size of the subgroups. This principle resembles the egalitarian school of thought, where the main goal is an equal allocation of resources to all subgroups (Pazner and Schmeidler, 1978). In a transport network criticality analysis context, this implies that the equity-weighted transport demand between any TAZ pair is equal, as we want to assign an equal importance to all subgroups. The weighting function is similar to the use of unweighted betweenness centrality in past transport network criticality studies (Aydin et al., 2018; Kermanshah and Derrible, 2016). The intuitive appeal of this principle for criticality is that it is completely agnostic to the actual transport demand. It provides an equal opportunity for all TAZs, irrespective of their socioeconomic attributes, to contribute in determining the criticality of the transport segments.

The equalization principle aims to ameliorate existing inequalities. It adheres to the Rawlsian maximin principle that puts a higher priority to the least advantaged population subgroups (Rawls, 2009). Accordingly, this principle requires imposing an equity multiplication factor to the transport demand. The equity multiplication factor imposed on a TAZ should be inversely proportional to the attribute size of that TAZ. To calculate this equity multiplication factor, an additional factor δ is introduced to characterize the inequality aversion preference of the decision makers. A higher factor implies a higher preference for inequality aversion. In the climate justice domain, inequality aversion factors ranging from 0 to 3 have been used, whereas the factors of 0.5 or 1 are the most often used (Adler et al., 2017; Anthoff et al., 2009; Hope, 2008). Various attributes of the TAZs can be used as the weighting variable w_i. These include transport-related attributes (e.g., accessibility of the TAZs, total transport flow originating from and coming to the TAZs, transport-induced pollution exposure of the TAZs) and socioeconomic attributes (e.g., total population, number of jobs, average income, degree of urbanization) of the TAZs (Kaplan et al., 2014; Sarlas et al., 2020).

There are two derivations of the equalization principle depending on the spatial scope of the attribute size comparison. In the global equalization approach, the attribute size of a TAZ is compared to the average attribute size of all TAZs. Another approach is the 'good neighbor' approach (Anthoff and Tol, 2010). This approach performs attribute size comparisons only among TAZs that are administratively (located within the same higher administrative unit) or spatially (located close to each other) related.

3.2. An adapted user equilibrium assignment

When assigning transport demand on top of the transport network, we have to distinguish the assignment of the actual physical

Table 1
Weighting functions for calculating equity-weighted transport demand.

Moral principle	School of thought behind the principle	Description	Weighting functions
Proportionality	Utilitarianism	Consideration to each TAZ is proportional to the level of the attribute size of the TAZ	$d^e_{ij} = d_{ij}$
Equality	Egalitarianism	Equal consideration to all TAZs regardless of the size of their attributes	$d^e_{ij} = \frac{d_{ij}}{d_{ij}}$
Equalization – global	Rawlsian maximin	Minimizing inequality between TAZs - consideration to each TAZ is inversely proportional to the size of the TAZ's attributes relative to all other TAZs	$d^e_{ij} = d_{ij} * \left(\frac{w_i}{\overline{w}}\right)^{-\delta} * \left(\frac{w_j}{\overline{w}}\right)^{-\delta}$; $\overline{w} = \frac{\sum_{i \in TAZ} w_i}{\lvert TAZ \rvert}$
Equalization – good neighbor	Rawlsian maximin	Minimizing inequality between TAZs that are administratively or spatially related	$d^e_{ij} = d_{ij} * \left(\frac{w_i}{\overline{w^n_i}}\right)^{-\delta} * \left(\frac{w_j}{\overline{w^n_j}}\right)^{-\delta}$; $\overline{w^n_i} = \frac{\sum_{j \in TAZ} w_j * n_{ij}}{\sum_{j \in TAZ} n_{ij}}$; $n_{ij} = \begin{cases} 1 & \text{TAZ } i \text{ and } j \text{ are related} \\ 0 & \text{Otherwise} \end{cases}$

where:
d^e_{ij}, equity-weighted transport demand between TAZ i and j
d_{ij}, original transport demand between TAZ i and j
w_i, attribute level/size of TAZ i
$\overline{w}$, average attribute level/size of all TAZs
$\overline{w^n_i}$, average attribute level/size of all TAZs that are administratively / spatially related with TAZ i
δ, inequality aversion factor.

Table 2
An adapted Frank-Wolfe algorithm for assigning equity-weighted demand. The original algorithm is adapted from Ortuzar and Willumsen (2011a), extra steps additional to the original algorithm are highlighted in red.

1	Initialization
2	for every link in the network
3	let $c_a = C_a(0)$ for all a
4	let $V_a^{o,n} = 0$ for all a and $n = 0$
5	let $V_a^{e,n} = 0$ for all a and $n = 0$
6	end for
7	Main loop
8	for $n = 1$ to maximum number of iterations
9	build minimum path trees with $V_a^{o,n-1}$ flow costs
10	load **T** all-or-nothing and obtain flows F_a^o and F_a^e
11	estimate ϕ to minimize Z
12	make $V_a^{o,n} = (1-\phi)V_a^{o,n-1} + \phi F_a^o$
13	make $V_a^{e,n} = (1-\phi)V_a^{e,n-1} + \phi F_a^e$
14	update $c_a = C_a(V_a^{o,n})$
15	if RG < 0.0001 stop
16	end for

where:
c_a, travel cost/time at the current flow on link a
$C_a(0)$, initial travel cost/time on link a
$V_a^{o,n}$, assigned original/physical demand on link a at iteration n
$V_a^{e,n}$, assigned equity-weighted demand on link a at iteration n
F_a^o, flow on link a after an all-or-nothing assignment of the original/physical demand
F_a^e, flow on link a after an all-or-nothing assignment of the equity-weighted demand
ϕ, weighting parameter to distribute current flow and flow from the previous iteration
Z, function of total travel cost
$C_a(V_a^{o,n})$, travel cost/time on link a when the flow on link a amounts to $V_a^{o,n}$
RG, relative gap between total travel cost of the current assignment and the previous assignment.

transport demand from the assignment of the equity-weighted transport demand. When using an all-or-nothing assignment, this distinction is not necessary since there is only one shortest route between each OD pair. However, when a congested or user equilibrium assignment is used, failure to distinguish the two kinds of demand would lead to erroneous assignment results. This is because, numerically speaking, the physical representation of the transport activities in the original transport demand is not maintained in the equity-weighted transport demand. For example, if the original transport demand between districts A and B are 100 units, it may become only 60 units in the equity-weighted OD matrix. This is in the case, for instance, when the equalization principle is adopted while districts A and B are relatively well-off compared to all other districts in the study area. Therefore, simply using the equity-weighted 60 units for the assignment algorithm would alter the physical equilibrium of the congestion on the network. To remedy this issue, a modified Frank-Wolfe algorithm for accounting equity-weighted transport demand in an equilibrium assignment is proposed (Table 2).

The main addition is the introduction of the equity-weighted transport demand assignment in parallel to the assignment of the original transport demand. The equity-weighted transport flow on each link is instantiated at the beginning of the algorithm (line 5 in Table 2). In each iteration, the equity-weighted assignment on each link is updated with the same congestion parameter ϕ as applied to the assignment of the original/physical demand (line 13 in Table 2). However, the update of each link's travel cost/time in each iteration is only based on the updated original demand assignment, instead of based on the equity-weighted demand assignment (line 14 in Table 2). In this way, the physical representation of transportation activities is maintained. At the same time, the step-wise assignment of the equity-weighted transport demand is executed in parallel to the step-wise assignment of its original/physical demand counterpart (lines 12 and 13 in Table 2). Although the presented modification in this study is specific for the Frank-Wolfe algorithm, the core principle of distinguishing the original transport demand from the equity-weighted transport demand is applicable to other equilibrium assignment algorithms.

4. Implementation: Bangladesh freight transport network analysis

I use the Bangladesh freight transport network model as a case study for illustrating the equity-based criticality analysis framework. This section provides a general overview of the context, background, and the model used in the study. For a more detailed explanation of the model readers are referred to Dappe et al. (2019a) and Jafino et al. (2020), whereas for a broader context of the case study readers are referred to Dappe et al. (2019b).

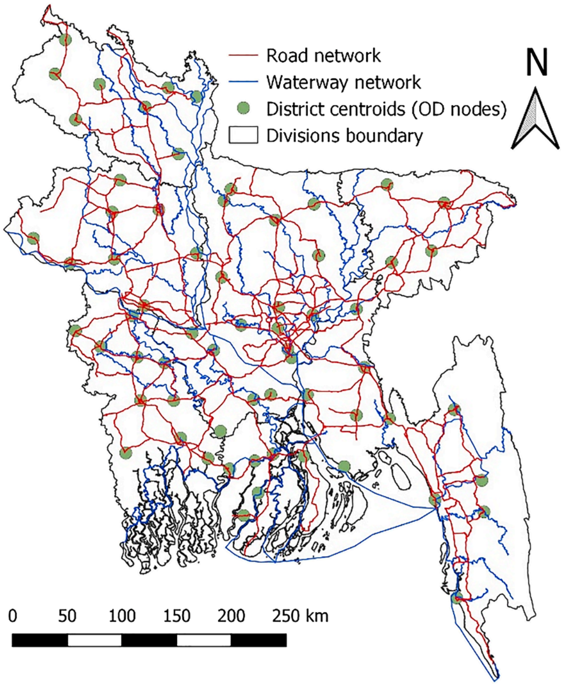

Fig. 3. Map of the case study.

4.1. Background

The Bangladesh freight transport network model simulates inter-district freight transport activities through roads and waterways in Bangladesh. There are three modules in the model: the transport network, the freight demand, and the trip assignment modules. A similar modelling approach was used in previous criticality analysis studies (e.g., Colon et al., 2019; Jafino et al., 2020; Jenelius and Mattsson, 2015; Rozenberg et al., 2017). The three modules make up the standard criticality analysis framework (i.e., the first row of Fig. 2) and were initially developed in Dappe et al. (2019a) and Jafino et al. (2020).

The transport network module consists of roads, inland waterways, and rivers. They are represented as nodes and links in the model (see Fig. 3). Railways are deliberately excluded since 96% of total freight transport activities are carried out through road and water (Smith, 2009). The Road and Highway Department of Bangladesh distinguishes three kinds of major roads. There are 3500 km of N (National) roads that connect the capital city of Dhaka with other divisions, 4200 km of R (Regional) roads that connect different districts with each other, and 13,500 km of Z (*Zilla*) roads that provide connection within a sub-district level. Since Z roads are mainly used for within-district transport activities, only N and R roads are considered in this study. The road network is extracted from the 2016 version of the Road Management and Maintenance System made available by the Road and Highway Department. The waterway network is derived from the inland waterway navigability assessment by Volgers et al. (2016). The transport network module also contains river ports and ferry *ghats* that act as transfer points between roads and waterways.

The freight demand module consists of an origin–destination (OD) matrix that contains transport demand information between the 64 districts in the country. In the model, each district is represented by a centroid node (see Fig. 3). Freight attraction and production in each district is estimated by an econometric model that combines information regarding surveyed amount of cargo and employment of freight-intensive sectors, the 2013 Economic Census Data, and the 2008 Agricultural Census. This includes, among others, agriculture, manufacturing, mining and quarrying, as well as wholesale trade. In total, there are approximately 38,000 medium truck equivalents of freight transport activities in the country in each day. A freight origin–destination synthesis (FODS) model is then used to construct the OD matrix from the district-level production and attraction data. The FODS model is a gravity based model that estimates an OD matrix while considering both loaded and empty trucks. A detailed account of the econometric model and the FODS model is provided in Dappe et al. (2019a).

The trip assignment module follows an equilibrium assignment method that distributes the transport demand on top of the transport network by using the Frank-Wolfe algorithm. Multimodality between land and water transport is accounted internally in the assignment. Therefore, freight transport demand between any two district can be satisfied by either land transport alone or by combinations of land and water transport. Additional costs of moving cargos and trucks between land and water are embedded on nodes that represent the river ports and ferry *ghats*. Since river ports have in general higher capacity compared to ferry *ghats,* the cargos handling time in river ports is assumed to be relatively lower than in ferry *ghats.* Fig. 4 shows the results of the equilibrium assignment performed in this study. The bolder the color, the more critical the segment is. To highlight the most critical segments in the network, links with criticality score higher than 0.1 are given a larger width on Fig. 4.

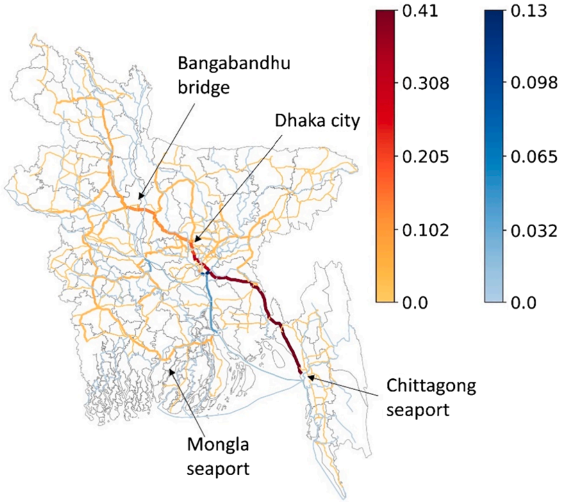

Fig. 4. Equilibrium assignment results. Red lines are road segments and blue lines are waterway segments. The numbers indicate the percentage of total freight flow traversing through the links. The upper thresholds used in the color scale correspond to the percentage of total freight flow in the most critical link. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The most critical transport segment for freight transport activities is the N1 corridor between Dhaka (the capital city) and Chittagong. The simulated average daily traffic on this corridor amounts to 15,580 medium truck equivalents. This corridor is critical due to two reasons. First, most of the population and most of the garment industries reside in the greater Dhaka region. Second, a large part (i.e., 90%) of import and export activities are carried out through the Chittagong seaport. Another critical segment is the Bangabandhu bridge on N405. This bridge is the only road segment that provides connection between districts in the northwest part of the country with the greater Dhaka region at the center of the country and ultimately with the Chittagong seaport in the far southeast.

From the perspective of transport authorities, results of criticality analysis are useful in supporting planning related to investment in road maintenance, lane extension, or quality improvement. Such investments would have further welfare implications to the population, as better accessibility to certain locations would reduce social inclusion and increase the attractiveness of that location for businesses (Currie and Delbosc, 2010; Dappe et al., 2019b; Lucas, 2012). In the context of planning for inter-district freight connectivity, better accessibility to rural areas has spatial spillover effects (Yu et al., 2013). It would not only enable local products to be transported to the rest of the country, but also potentially connect them to international markets as they get better connected with the Chittagong seaport. One transport intervention that has led to a large welfare impacts in Bangladesh is the construction of the Bangabandhu bridge. The construction of this bridge has led to an increase in agricultural productivity not only in areas adjacent to the bridge but also in rural areas further to the northwest of the bridge (Blankespoor et al., 2018), as they are now connected to the big agricultural market around Dhaka.

The choice of moral principles underlying the transport network criticality analysis would perceptibly have different distributive consequences to the planning. For example, adopting the proportionality principle would lead to allocation of resources to the currently busy roads, which then could foster further densification of industries in the already urbanized districts. On the contrary, the use of the equalization principle would favor road segments that provide connection to rural and deprived areas. Such a prioritization has a potential of inducing long-term spatial spillover effect that could benefit those rural areas.

4.2. Study design

The computational experiment of the case study aims to understand how using different moral principles affects the criticality results, i.e., the ranking of links in the transport network. This experiment is divided into three parts. The first part observes the implications of using the four moral principles as presented in Table 1. The inequality aversion factor δ of 1 is used for the two equalization principles in this first part, whereas a transport-related variable of total freight flow from and to each district is used as the weighting variable w_i. The second and the third part zoom in to the global equalization principle. The effects of using different values for the inequality aversion factor is observed in the second part. The third part observes the implications of using alternative weighting variables, including total number of establishments, total population, and household vulnerability index in each district (Bangladesh Bureau of Statistics, 2013, 2015, 2018). Before presenting the criticality results, the equity-weighted OD matrix based on the different moral principles is first reported.

The link-level criticality scores from the different moral principles are compared by using the Spearman-rank correlation coefficient. This correlation coefficient estimates the agreement of ranking between elements of two sets, instead of the agreement of their actual values. The higher the rank correlation between criticality results from two moral principles, the more similar the set of links identified as critical is. The main reason to use the Spearman-rank correlation coefficient is because of the purpose of a criticality analysis, which is to rank all segments in a transport network (Jafino et al., 2020; Knoop et al., 2012). Hence, of more relevance is whether one segment is more important than the other, rather than the actual criticality score of that segment. This purpose suits the nature of Spearman-rank correlation coefficient that focuses on the monotonicity of rankings of elements from two different sets. The use of Spearman-rank correlation coefficient to measure the monotonic association between rankings of elements from two different criticality metrics can also be found in previous studies (Chen et al., 2012; Knoop et al., 2012; Luathep et al., 2011; Scott et al., 2006).

The Spearman-rank correlation coefficient is calculated only for a subset of links in the network. There are two filters to end up with this subset of link. First, only links which criticality score is higher than zero are accounted. Second, for comparisons of any pair of moral principles, only the 100 most critical links from each moral principle are accounted. This is because there are many links which are not assigned with any transport flow by the user equilibrium assignment. These links are primarily used for within district, rather than between-district, transport activities. As the contribution of these links to the inter-district freight transport activities is relatively small, including them would produce noise in the comparison of the criticality results.

5. Results

5.1. Comparative analysis between different moral principles

Fig. 5 displays the normalized equity-weighted OD matrices based on the proportionality, equity, global equalization, and good

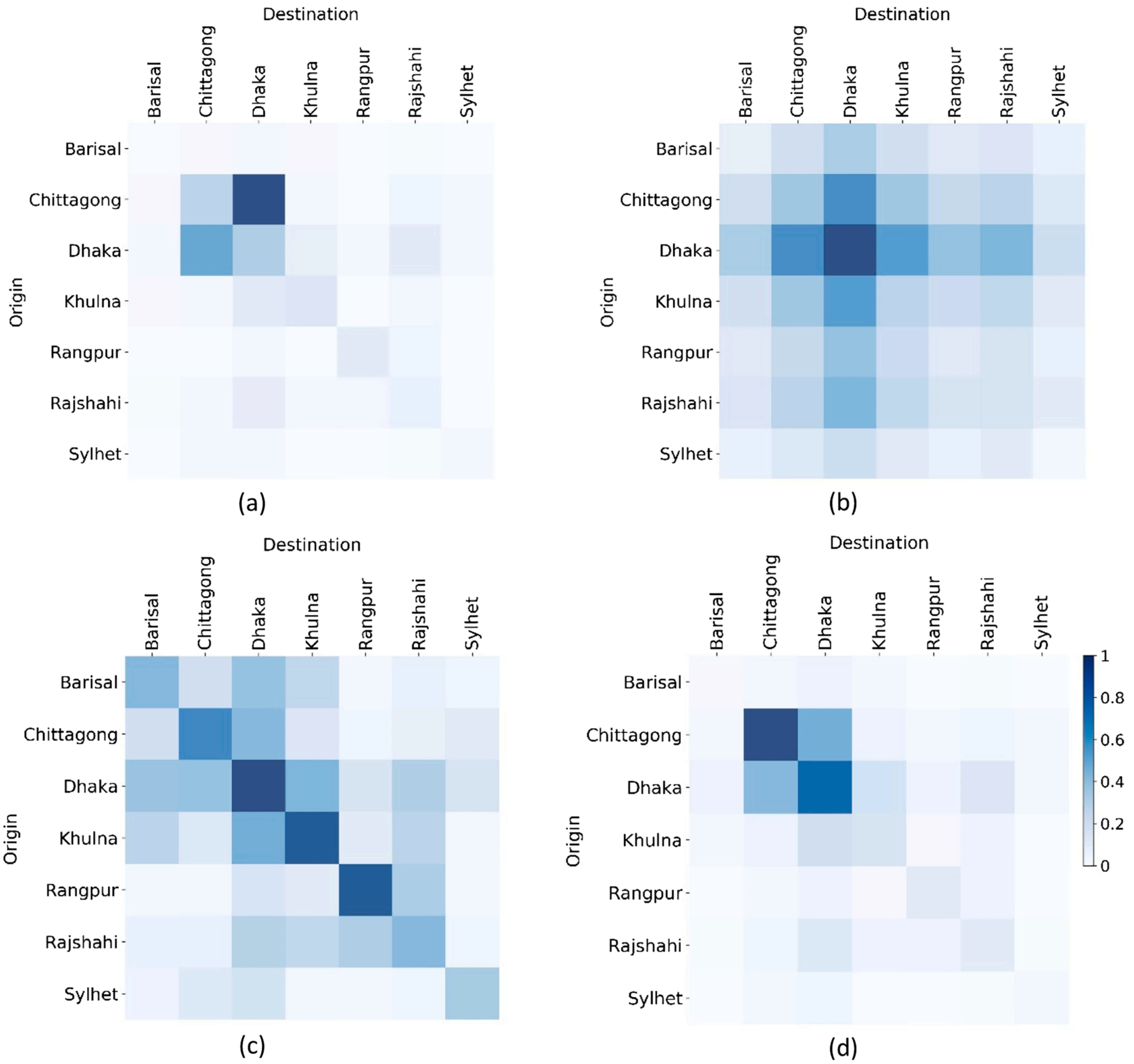

Fig. 5. Division-level equity-weighted OD matrices based on the (a) proportionality principle, (b) equality principle, (c) global equalization principle, (d) 'good neighbor' equalization principle. The transport demand in each matrix is normalized between 0 and 1.

neighbor equalization principles. The OD matrices are presented at the division level, which is one administrative level higher than the district level. Hence, the transport demand from the 64 districts are aggregated into 7 divisions. The proportionality principle weighted OD matrix is basically similar to the original OD matrix since there is no additional weighting factors applied. In line with the equilibrium assignment results on Fig. 4, the transport activities between Dhaka and Chittagong dominate the freight transport demand. The equality principle weighted OD matrix (Fig. 5b) has a uniform equity-weighted demand of 1 between all districts pairs. The higher transport demand from Dhaka division on Fig. 5b is caused by the larger number of districts in the division. While there are 17 districts in Dhaka division, there are only 11 districts in Chittagong, 10 districts in Khulna, 8 districts in Rajshahi and Rangpur, 6 districts in Barisal and 4 districts in Sylhet.

The use of the global equalization principle results in a distinctive OD pattern (Fig. 5c). While the equity-weighted demand between districts in Dhaka division is still the dominant one, new hotspots of equity-weighted demand emerge for Khulna and Rangpur divisions, which are located in the southwest and northwest part of the country. These divisions are relatively rural compared to Dhaka and Chittagong, and therefore have far fewer total freight flow (Blankespoor et al., 2018; Dappe et al., 2019c). Since total freight flow is used as the weighting variable, these divisions get a higher equity multiplication factor that substantially increases their equity-weighted transport demand.

The good neighbor equalization principle results in an OD matrix that has a similar pattern with the proportionality principle (Fig. 5d). One explanation behind this is the similar total freight flow among districts that are located within the same division. As a result, the equity multiplication factors for these districts do not substantially alter the districts' original demand. An exception is for Chittagong division. Here, Chittagong district has a substantially higher total freight flow compared to other districts in the same division. The high within-division inequality increases the equity-weighted transport demand of districts in Chittagong division.

Fig. 6 shows the pairwise comparisons of links ranking from the criticality results of the four different moral principles. Each point in the figure corresponds to the criticality ranks of a link based on two moral principles. Links with higher ranks (i.e., closer to 1) have higher criticality scores, and hence are more important. If criticality results from two moral principles yield the exactly same ranking of links, all points would line up along the grey diagonal dashed line. If a point resides above this dashed line, the link represented by that point has a lower rank based on the moral principle in the vertical axis compared to the moral principle in the horizontal axis. Contrariwise, points below the diagonal axis have a higher rank based on the moral principle in the vertical axis compared to the principle in the horizontal axis. The closer a point to the diagonal line, then the smaller the ranking difference of that point when assessed from the two moral principles is.

The low correlation coefficients in Fig. 6 imply that there are no pairs of moral principles that indicate similar sets of links as critical. The highest ranking coefficient of 0.48 is observed for the criticality results from the equality principle and the good neighbor equalization principle. Even in this highest correlated pair, there are some links which rank higher than 100 based on the good neighbor equalization principle, whereas they rank lower than 200 in the equality principle (Fig. 6e). Similar divergence patterns are also observed in other pairs of moral principles (Fig. 6a-c). In Fig. 6c, for instance, there is one link that ranks approximately 50 in the good neighbor principle, but it ranks around 400 in the proportionality principle. This result also shows that even a slight distortion of OD matrix patterns (e.g., the equity-weighted OD matrices from the proportionality principle and the good neighbor equalization

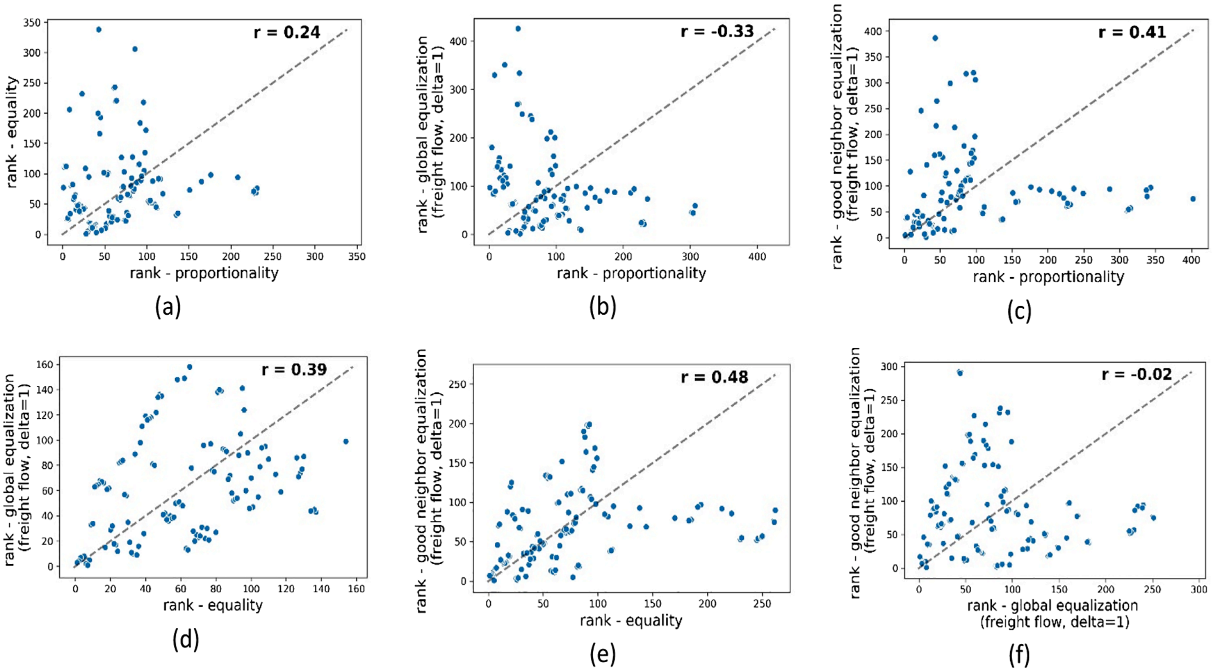

Fig. 6. Ranking correlations among criticality results of the four different moral principles along with their Spearman-rank correlation coefficient.

principle in Fig. 5a and d) could result in substantially different rankings of transport network components.

Fig. 7 visualizes the criticality results from each moral principle. Criticality results from the proportionality principle (Fig. 7a) have an exactly similar spatial pattern as the equilibrium assignment results (Fig. 4) since there is no modification to the original OD matrix. The use of the equality principle, which gives each district the same equity-weighted flow, shifts the most critical segment to the Jamuna/Bangabandhu bridge which is located at the northwest of Dhaka (Fig. 7b). This bridge provides the only road connection between districts in the northwestern part to districts in the eastern part of the country (Ahmad et al., 2003), and has been attributed to the decreasing disparity between the two regions (Blankespoor et al., 2018; Mahmud and Sawada, 2018). The use of the global equalization principle makes road segments in the eastern part of the country not critical anymore (Fig. 7c). The critical segments are now located in the western part of the country. This is due to the higher equality multiplication factors that are given to freight flow from and to rural districts which are mainly located in the far northwest and southwest.

5.2. Impacts of preferences to inequity aversion

The use of a higher value for the inequality aversion factor δ would amplify the weight given to transport demand from and to each district based on the inequality of the weighting variable w_i. The use of a lower δ, on the contrary, would dampen the weight given to the transport demand. Fig. 8 displays the equity-weighted OD matrices based on the global equalization principle with different inequality aversion factors. The figure shows the shifting pattern of the equity-weighted OD matrix when higher values for δ are used. With $\delta = 0.5$, the pattern of the equity-weighted OD matrix (Fig. 8a) still resembles some pattern that exist in the original OD matrix (Fig. 5a). Equity-weighted transport demand between Chittagong and Dhaka divisions still dominates the OD matrix, although new large equity-weighted transport demand starts to appear in the other divisions. This is because only small emphasis is given to the inequality among districts. With $\delta = 1$, the domination of transport demand between Chittagong and Dhaka divisions starts to be surpassed with transport demand of other divisions (Fig. 8b). Lastly, with $\delta = 2$, an even higher emphasis is given to the inequality among the districts. Transport demand between districts in Barisal division dominates the OD matrix since this district has the lowest weighting variable w_i.

The comparison of the criticality results from these three different inequality patterns is presented in Fig. 9. As can be roughly guessed from the OD matrices, none of the criticality results produced by the three different inequality aversion factors yield the same

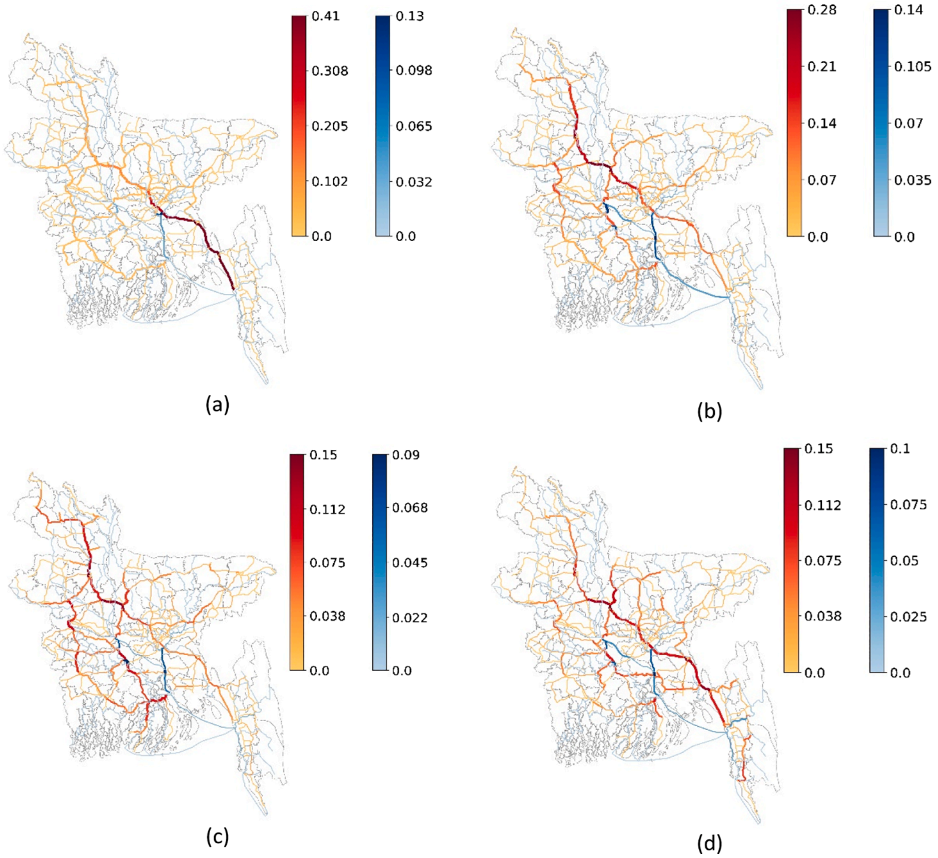

Fig. 7. Equity-weighted criticality results based on the (a) proportionality, (b) equality, (c) global equalization, and (d) good neighbor equalization principles. Red lines are road segments and blue lines are waterway segments. The numbers indicate the fraction of the total equity-weighted freight flow traversing through the links. The upper thresholds used in the color scale correspond to the equity-weighted criticality score in the most critical link. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

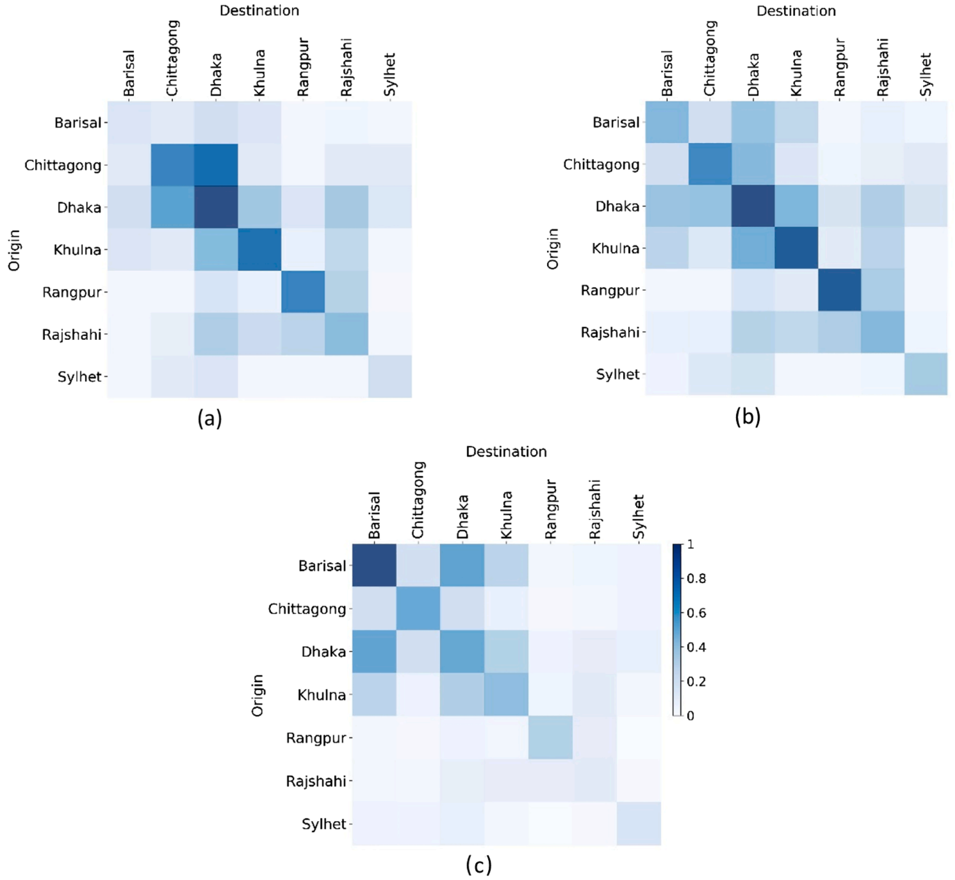

Fig. 8. Division-level equity-weighted OD matrices based on the global equalization principle, with inequality aversion factor of (a) 0.5, (b) 1, (c) 2. The transport demand in each matrix is normalized between 0 and 1.

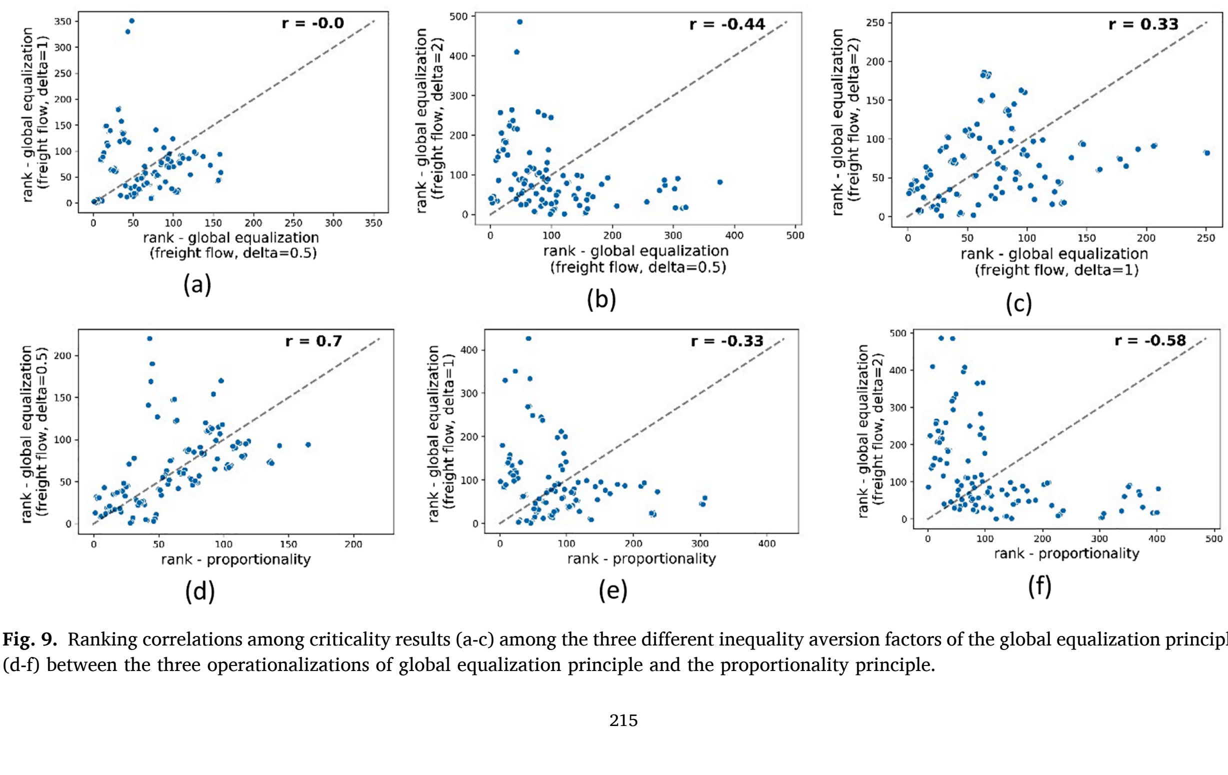

Fig. 9. Ranking correlations among criticality results (a-c) among the three different inequality aversion factors of the global equalization principle, (d-f) between the three operationalizations of global equalization principle and the proportionality principle.

ranking of links (Fig. 9a-c). The highest correlation is observed between criticality results from $\delta = 1$ and $\delta = 2$ (Fig. 9c). Even between these two criticality results, many of the points in Fig. 9c are not located near the diagonal dashed line, implying that the differences in ranking of the individual links are relatively high. Comparing the three operationalizations of the global equalization principle with the proportionality principle reveals a different pattern (Fig. 9d-f). Here, a higher inequality aversion factor leads to an even lower rank correlation with the proportionality principle.

5.3. Impacts of alternative weighting variables

Fig. 10 presents the equity-weighted OD matrices from the use of different weighting variables in the global equalization principle. The use of alternative weighting variables creates an OD matrix with a pattern that is distinct from the original OD matrix (Fig. 5a). An exception is the OD matrix from the use of the household vulnerability index (Fig. 10b). This OD matrix is similar to the original OD matrix because the range of the distribution of the household vulnerability indices among districts is not as large as the range of the distribution of the other weighting variables. Furthermore, districts with the highest household vulnerability index are mainly located in the Chittagong division (Bangladesh Bureau of Statistics, 2015), hence a higher equity weight is given to transport demand involving

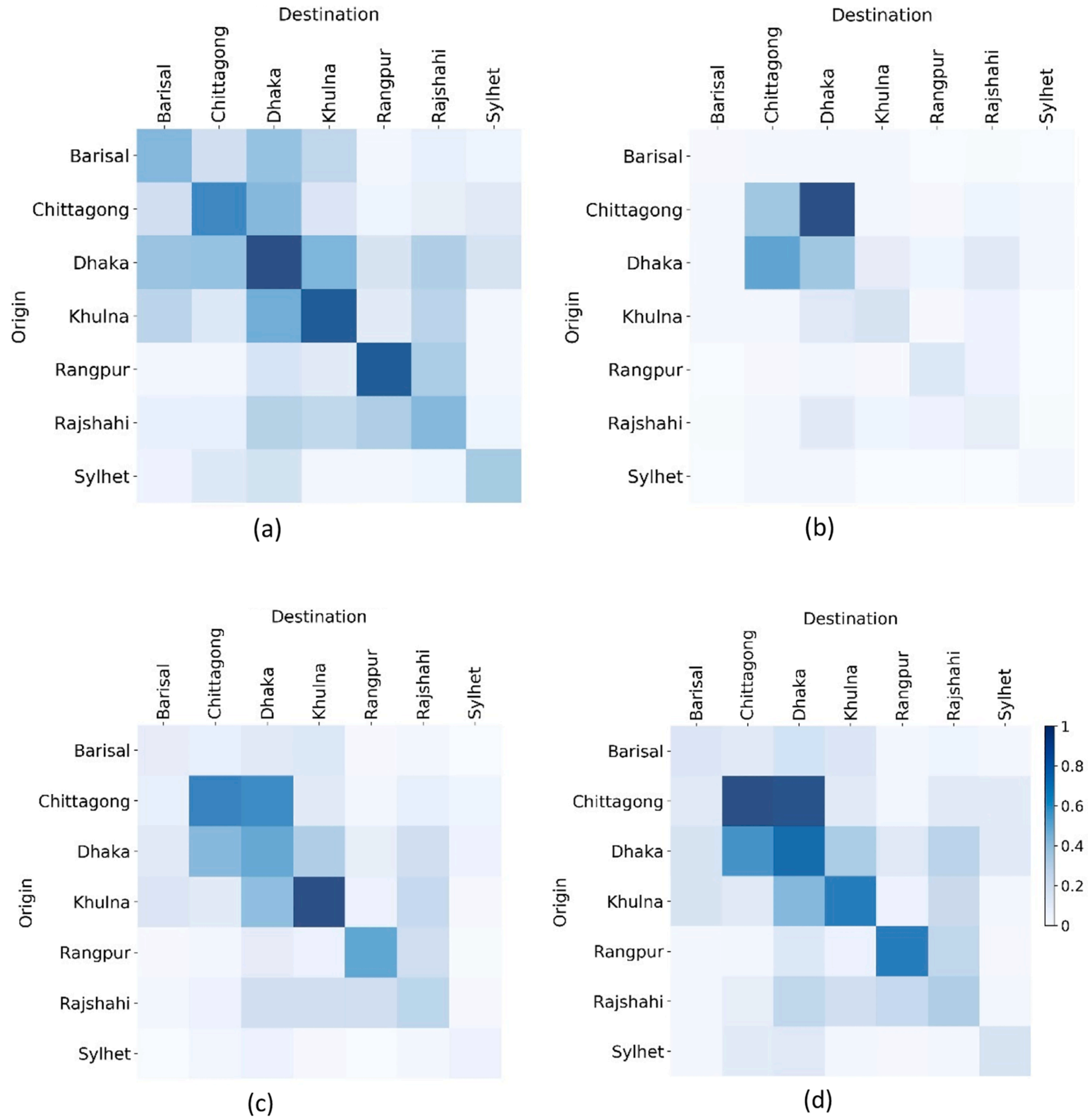

Fig. 10. Division-level equity-weighted OD matrices based on the global equalization principle using different weighting variables: (a) total freight flow, (b) household vulnerability index, (c) total population, (d) number of establishments. The transport demand in each matrix is normalized between 0 and 1.

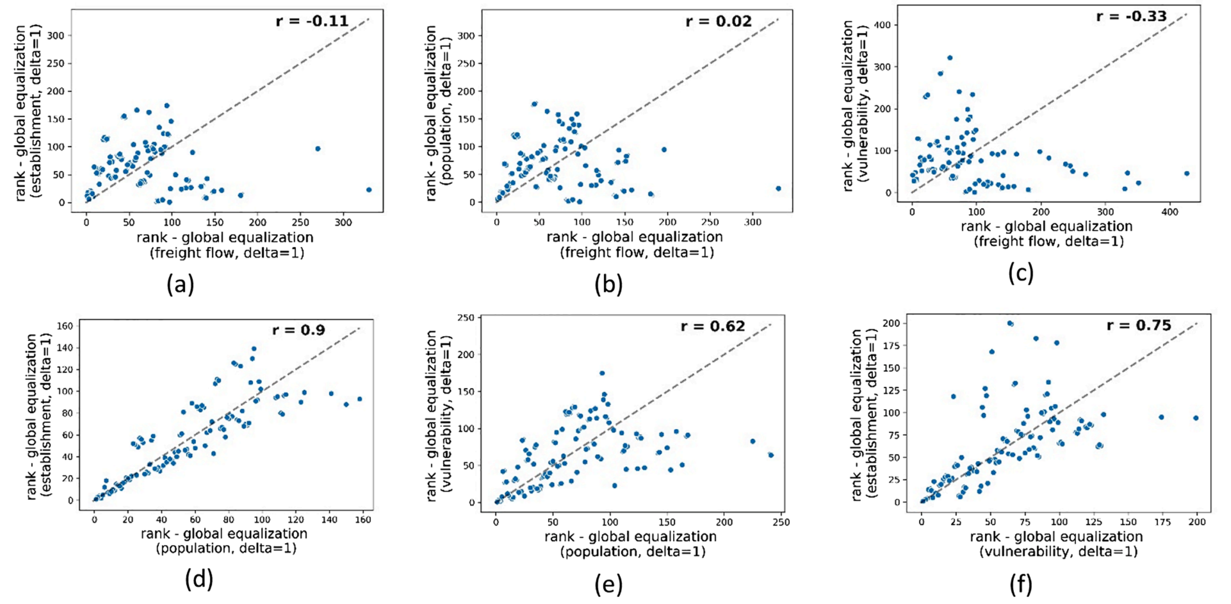

Fig. 11. Ranking correlations among criticality results from the four different weighting variables applied to the global equalization principle.

this division. The patterns of OD matrices from the use of total population and number of establishment as weighting variables are quite similar (Fig. 10c-d). In the latter, however, equity-weighted transport demand involving Dhaka and Chittagong divisions are still dominating the OD pattern.

The results of the criticality rankings comparison are exhibited in Fig. 11. Criticality results from the use of freight flow as weighting variable do not have high ranking similarity with criticality results from the other three weighting variables (Fig. 11a-c). The lowest ranking correlation is observed between criticality results from the use of freight flow and the use of household vulnerability index as weighting variable (Fig. 11c).

The highest ranking correlation is observed between criticality results from the use of total population and number of establishment as weighting variables (Fig. 11d), with a Spearman-rank correlation coefficient of 0.9. An explanation for this can be inferred from the equity-weighted OD matrices from the use of these two weighting variables (Fig. 10c-d). The OD matrices have a similar pattern, although the most dominant equity-weighted transport demand based on the use of total population as weighting variable is those involving Khulna division, whereas based on the use of number of establishments the dominant demand is still those involving Chittagong and Dhaka division.

Criticality results from the use of household vulnerability index also have relatively high rank correlations with criticality results from the use of the total population and number of establishments (Fig. 11e-f), despite the presence of some outliers. This can also be reasoned back from their equity-weighted OD matrices. In all three OD matrices (Fig. 10b-d), the equity-weighted demand of freight activities involving Dhaka and Chittagong divisions is relatively high. In the equity-weighted OD matrix from the use of the freight flow as weighting variable (Fig. 10a), on the contrary, the highest transport demand is observed for the within-division freight activities in Dhaka, Khulna, and Rangpur divisions.

6. Discussion and conclusion

While the use of transport network criticality analysis to support transport planning and decision-making is increasing, reflection on the distributive moral principle underlying the analysis is only minimally, if at all, done. Many criticality studies implicitly assume a utilitarian principle where the aim is to maximize the aggregate benefit to all transport users (Jafino et al., 2020). Such a principle is blind to the distribution of costs and benefits to the different users. This risks exacerbating existing inequalities or even introducing new inequalities. To remedy this issue, this paper proposes an equity-based transport network criticality analysis framework. This framework requires one to select and reflect on an appropriate distributive moral principle before conducting criticality analysis. There are two main differences between this framework and the standard criticality analysis workflow. The first is the calculation of an equity-weighted transport demand based on certain distributive moral principles. To this end, four alternative moral principles that are specific for the transport domain have been operationalized: proportionality, equality, global equalization, and good neighbor equalization. The second difference is the adjustment of the Frank-Wolfe equilibrium assignment, so that the actual physical representation of the transport activities is maintained while the equity-weighted transport demand is iteratively assigned on the network.

This paper provides an application of the equity-based criticality analysis framework for an inter-district freight transport network case study in Bangladesh. The rankings of transport network components produced by the operationalization of each moral principle are compared. The results show a shift of transport segments criticality rankings when different moral principles are used. A transport segment that belongs to the top 10 most critical links based on one moral principle can rank further than 100 when another moral principle is used. Criticality rankings from several pairs of moral principles even have a negative rank correlation, implying that the more critical a transport segment is in one moral principle the less critical that segment is in the other moral principle. When equalization principles are adopted, the choice of the weighting variable (what socioeconomic attributes of the transport users do we want to consider for equalization?) and the inequality aversion factor (to what extent do we want to emphasize on the inequality?) strongly affects the criticality rankings. The results also indicate that the ranking similarity from two different moral principles can to some extent be inferred from the corresponding moral principles' equity-weighted OD matrices.

In the context of inter-district freight transport planning, criticality analysis results are useful for prioritizing interventions such as maintenance, road quality improvement, and lane extension. From a transport authority and planner perspective, reduction of logistical cost due to such interventions could have spillover effects through multiple channels: reducing commodity prices in affected areas, opening up new market opportunities for existing businesses, and increasing the attractiveness of affected areas to new businesses (Álvarez-Ayuso et al., 2016; López et al., 2009; Yu et al., 2013; Yu et al., 2016). Consequently, the choice of moral principles underlying a criticality analysis could have a second order effect to how economic activities move from one region to another. To this end, many previous freight transport network criticality analysis studies implicitly adopted the proportionality principle without deliberating the distributional consequences of their choice (see e.g., Ashrafi et al., 2017; Burgholzer et al., 2013; Colon et al., 2019; Madar et al., 2020; Rozenberg et al., 2017).

In the Bangladesh example, adopting the utilitarian principle would result in more resources allocated on the N1 highway between Dhaka and Chittagong. This could reinforce industry agglomeration around the two cities. Adopting the equality principle shifts the criticality hotspots to the N4, N405, and N5 highways that connect the northern districts to the rest of the country. The use of the global equalization principle highlights the importance of smaller roads in the western and southwestern part of the country, owing to the fact that districts in this area are relatively more deprived. Using either equality or global equalization principles could therefore have long-term consequences to the inter-district inequality in the country. This finding exemplifies a typical moral dilemma that decision makers should face in planning transport infrastructure.

The results of the case study reveal two further general policy-relevant insights applicable for future equity-based transport network criticality studies. First, in doing criticality analysis it is imperative for one to start with the policy question at hand and then reflect on a relevant moral principle to use. When the aim is simply to improve the overall functioning of the transport network system, one might adopt the utilitarian principle. When the objective is to provide equal resources to all transport users (which are aggregated at a certain Transportation Analysis Zone), the equality principle becomes more appropriate to use. The equalization principle is more suitable when the question at hand is how to prioritize resources for worse-off transport users. Overlooking the selection of the moral principle at the beginning of a study could result in unintended distributional consequences.

The second insight concerns the selection of the weighting variables. Since the use of different weighting variables within the equalization principle might produce distinctive criticality rankings, the contextual factors of the criticality analysis should be used to determine what attributes to use as weighting variable. For example, when prioritizing road infrastructure reparation after disasters we might want to give precedence to transport users who are at risk. Hence, the disaster resiliency capacity of the transport users is relevant to use as the weighting variable, and the equalization principle should be adopted (so that higher weights would be given to transport demand from subgroups with low resilience capacity or high vulnerability). Looking at the case study in this paper, for instance, this means using the equalization principle with the household vulnerability index as the weighting variable (see Section 5.3). These two insights support previous studies that have emphasized the importance of a normative approach in doing transport planning and network analysis (Jafino et al., 2020; Jenelius and Mattsson, 2015).

The equity-weighted criticality analysis framework is constructed assuming the use of betweenness centrality as the criticality metric and the use of Frank-Wolfe algorithm for the equilibrium assignment. An adaptation to this framework is required when other criticality metrics and assignment algorithms, such as the interdiction criticality, are being used. It is important to note here that the choice of criticality metric could lead to a different choice of the *unit* of the distribution. Furthermore, the four moral principles used in this study are general distributive principles found in the field of transport equity (Martens et al., 2019). These principles and the individual use of these principles might not be exhaustive enough for all kinds of transport planning problems. For instance, when planning for road lanes extension, one might want to balance between maximizing the total benefits and minimizing pollution exposure to vulnerable groups (Pereira et al., 2016; Van Wee and Roeser, 2013). Doing equity-based criticality analysis for such planning problems might need composite indicators stemming from multiple distributive principles. Lastly, from a more methodological point of view, there is an indication that the similarity of the criticality results between two different moral principles can be inferred from the corresponding equity-weighted OD matrices. To this end, more case studies could be conducted to investigate the correlation between OD matrix similarities and criticality ranking similarities.

CRediT authorship contribution statement

Bramka Arga Jafino: Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing - original draft, Writing - review & editing, Visualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Adler, M., Anthoff, D., Bosetti, V., Garner, G., Keller, K., Treich, N., 2017. Priority for the worse-off and the social cost of carbon. Nat. Clim. Change 7 (6), 443–449. https://doi.org/10.1038/nclimate3298.

Ahmad, I., Azhar, S., Ahmed Syed, M., 2003. Construction of a bridge in a developing country: A Bangladesh case study. Leadersh. Manage. Eng. 3 (4), 177–182. https://doi.org/10.1061/(ASCE)1532-6748(2003)3:4(177).

Almotahari, A., Yazici, A., 2020. Impact of topology and congestion on link criticality rankings in transportation networks. Transp. Res. Part D: Transport Environ. 87, 102529 https://doi.org/10.1016/j.trd.2020.102529.

Álvarez-Ayuso, I.C., Condeço-Melhorado, A.M., Gutiérrez, J., Zofío, J.L., 2016. Integrating network analysis with the production function approach to study the spillover effects of transport infrastructure. Regional Studies 50 (6), 996–1015. https://doi.org/10.1080/00343404.2014.953472.

Anthoff, D., Tol, R.S.J., 2010. On international equity weights and national decision making on climate change. J. Environ. Econ. Manage. 60 (1), 14–20. https://doi.org/10.1016/j.jeem.2010.04.002.

Anthoff, D., Tol, R.S.J., Yohe, G.W., 2009. Risk aversion, time preference, and the social cost of carbon. Environ. Res. Lett. 4 (2), 024002 https://doi.org/10.1088/1748-9326/4/2/024002.

Ashrafi, Z., Shahraki, H.S., Bachmann, C., Gingerich, K., Maoh, H., 2017. Quantifying the criticality of highway infrastructure for freight transportation. Transp. Res. Rec. 2610 (1), 10–18. https://doi.org/10.3141/2610-02.

Atteridge, A., Remling, E., 2018. Is adaptation reducing vulnerability or redistributing it? Wiley Interdiscip. Rev. Clim. Change 9 (1), e500. https://doi.org/10.1002/wcc.500.

Aydin, N.Y., Casali, Y., Sebnem Duzgun, H., Heinimann, H.R., 2019. Identifying changes in critical locations for transportation networks using centrality. In: Geertman, S., Zhan, Q., Allan, A., Pettit, C. (Eds.), Computational Urban Planning and Management for Smart Cities. Springer International Publishing, New York, pp. 405–423.

Aydin, N.Y., Duzgun, H.S., Wenzel, F., Heinimann, H.R., 2018. Integration of stress testing with graph theory to assess the resilience of urban road networks under seismic hazards. Nat. Hazards 91 (1), 37–68. https://doi.org/10.1007/s11069-017-3112-z.

Balijepalli, C., Oppong, O., 2014. Measuring vulnerability of road network considering the extent of serviceability of critical road links in urban areas. J. Transp. Geogr. 39, 145–155. https://doi.org/10.1016/j.jtrangeo.2014.06.025.

Bangladesh Bureau of Statistics, 2013. District statistics. http://www.bbs.gov.bd/site/page/2888a55d-d686-4736-bad0-54b70462afda/District-Statistics.

Bangladesh Bureau of Statistics, 2015. Population density and vulnerability: A challange for sustainable development of Bangladesh. http://203.112.218.65:8008/WebTestApplication/userfiles/Image/PopMonographs/Volume-7_PDV.pdf.

Bangladesh Bureau of Statistics, 2018. Statistical Yearbook of Bangladesh 2018. http://bbs.portal.gov.bd/sites/default/files/files/bbs.portal.gov.bd/page/b2db8758_8497_412c_a9ec_6bb299f8b3ab/SYB-2018.pdf.

Baroud, H., Barker, K., Ramirez-Marquez, J. E., & Rocco S., C. M., 2014. Importance measures for inland waterway network resilience. Transportation Research Part E: Logistics and Transportation Review, 62, 55-67. doi:10.1016/j.tre.2013.11.010.

Behbahani, H., Nazari, S., Jafari Kang, M., Litman, T., 2019a. A conceptual framework to formulate transportation network design problem considering social equity criteria. Transp. Res. Part A: Policy Practice 125, 171–183. https://doi.org/10.1016/j.tra.2018.04.005.

Behbahani, H., Nazari, S., Partovifar, H., Kang Masood, J., 2019b. Designing a road network using John Rawls's social justice approach. J. Urban Plann. Dev. 145 (2), 05019002. https://doi.org/10.1061/(ASCE)UP.1943-5444.0000500.

Bell, D., 2004. Environmental justice and Rawls' difference principle. Environ. Ethics 26 (3), 287–306.

Ben-Elia, E., Benenson, I., 2019. A spatially-explicit method for analyzing the equity of transit commuters' accessibility. Transp. Res. Part A: Policy Practice 120, 31–42. https://doi.org/10.1016/j.tra.2018.11.017.

Beyazit, E., 2011. Evaluating social justice in transport: lessons to be learned from the capability approach. Transport Rev. 31 (1), 117–134. https://doi.org/10.1080/01441647.2010.504900.

Beyazit, E., 2015. Are wider economic impacts of transport infrastructures always beneficial? Impacts of the Istanbul Metro on the generation of spatio-economic inequalities. J. Transp. Geogr. 45, 12–23. https://doi.org/10.1016/j.jtrangeo.2015.03.009.

Blankespoor, B., Emran, M.S., Shilpi, F., Xu, L., 2018. Bridge to Bigpush or Backwash? Market Integration, Reallocation, and Productivity Effects of Jamuna Bridge in Bangladesh. The World Bank, Washington D.C.

Bocarejo, J.P., Oviedo, D.R., 2012. Transport accessibility and social inequities: a tool for identification of mobility needs and evaluation of transport investments. J. Transp. Geogr. 24, 142–154. https://doi.org/10.1016/j.jtrangeo.2011.12.004.

Burgholzer, W., Bauer, G., Posset, M., Jammernegg, W., 2013. Analysing the impact of disruptions in intermodal transport networks: A micro simulation-based model. Decis. Support Syst. 54 (4), 1580–1586. https://doi.org/10.1016/j.dss.2012.05.060.

Cats, O., Jenelius, E., 2016. Beyond a complete failure: the impact of partial capacity degradation on public transport network vulnerability. Transportmetrica B: Transport Dyn. 6 (2), 77–96. https://doi.org/10.1080/21680566.2016.1267596.

Cats, O., Krishnakumari, P., 2020. Metropolitan rail network robustness. Phys. A 124317. https://doi.org/10.1016/j.physa.2020.124317.

Chen, B.Y., Lam, W.H.K., Sumalee, A., Li, Q., Li, Z.-C., 2012. Vulnerability analysis for large-scale and congested road networks with demand uncertainty. Transp. Res. Part A: Policy Practice 46 (3), 501–516. https://doi.org/10.1016/j.tra.2011.11.018.

Colon, C., Hallegatte, S., Rozenberg, J., 2019. Transportation and Supply Chain Resilience in the United Republic of Tanzania. World Bank.

Currie, G., Delbosc, A., 2010. Modelling the social and psychological impacts of transport disadvantage. Transportation 37 (6), 953–966.

Dappe, M.H., Kunaka, C., Lebrand, M., Weisskopf, N., 2019a. Freight demand. In: Moving Forward: Connectivity and Logistics to Sustain Bangladesh's Success. The World Bank, Washington D.C., pp. 17–50

Dappe, M.H., Kunaka, C., Lebrand, M., Weisskopf, N., 2019b. Moving Forward: Connectivity and Logistics to Sustain Bangladesh's Success. The World Bank, Washington D.C.

Dappe, M.H., Kunaka, C., Lebrand, M., Weisskopf, N., 2019c. Successful albeit poor logistics performance. In: Moving Forward: Connectivity and Logistics to Sustain Bangladesh's Success. The World Bank, Washington D.C., pp. 9–16

de Jong, G., Vierth, I., Tavasszy, L., Ben-Akiva, M., 2013. Recent developments in national and international freight transport models within Europe. Transportation 40 (2), 347–371. https://doi.org/10.1007/s11116-012-9422-9.

De Oliveira, E.L., da Silva Portugal, L., Junior, W.P., 2016. Indicators of reliability and vulnerability: Similarities and differences in ranking links of a complex road system. Transp. Res. Part A: Policy Practice 88, 195–208.

Dehghani, M.S., Flintsch, G., McNeil, S., 2014. Impact of road conditions and disruption uncertainties on network vulnerability. J. Infrastruct. Syst. 20 (3) https://doi.org/10.1061/(ASCE)IS.1943-555X.0000205.

Delbosc, A., Currie, G., 2011a. The spatial context of transport disadvantage, social exclusion and well-being. J. Transp. Geogr. 19 (6), 1130–1137. https://doi.org/10.1016/j.jtrangeo.2011.04.005.

Delbosc, A., Currie, G., 2011b. Using Lorenz curves to assess public transport equity. J. Transp. Geogr. 19 (6), 1252–1259. https://doi.org/10.1016/j.jtrangeo.2011.02.008.

Delmelle, E.C., Casas, I., 2012. Evaluating the spatial equity of bus rapid transit-based accessibility patterns in a developing country: The case of Cali, Colombia. Transp. Policy 20, 36–46. https://doi.org/10.1016/j.tranpol.2011.12.001.

Demirel, H., Kompil, M., Nemry, F., 2015. A framework to analyze the vulnerability of European road networks due to Sea-Level Rise (SLR) and sea storm surges. Transp. Res. Part A: Policy Practice 81, 62–76. https://doi.org/10.1016/j.tra.2015.05.002.

Di Ciommo, F., Shiftan, Y., 2017. Transport equity analysis. Transp. Rev. 37 (2), 139–151. https://doi.org/10.1080/01441647.2017.1278647.

Du, Q., Kishi, K., Aiura, N., Nakatsuji, T., 2014. Transportation network vulnerability: vulnerability scanning methodology applied to multiple logistics transport networks. Transp. Res. Rec.: J. Transp. Res. Board 2410, 96–104.

Espinet, X., Rozenberg, J., 2018. Prioritization of climate change adaptation interventions in a road network combining spatial socio-economic data, network criticality analysis, and flood risk assessments. Transp. Res. Rec. 2672 (2), 44–53. https://doi.org/10.1177/0361198118794043.

Espinet, X., Schweikert, A., van den Heever, N., Chinowsky, P., 2016. Planning resilient roads for the future environment and climate change: Quantifying the vulnerability of the primary transport infrastructure system in Mexico. Transp. Policy 50, 78–86. https://doi.org/10.1016/j.tranpol.2016.06.003.

Foth, N., Manaugh, K., El-Geneidy, A.M., 2013. Towards equitable transit: examining transit accessibility and social need in Toronto, Canada, 1996–2006. J. Transp. Geogr. 29, 1–10. https://doi.org/10.1016/j.jtrangeo.2012.12.008.

France-Mensah, J., Kothari, C., O'Brien, W.J., Jiao, J., 2019. Integrating social equity in highway maintenance and rehabilitation programming: A quantitative approach. Sustain. Cities Soc. 48, 101526 https://doi.org/10.1016/j.scs.2019.101526.

Gauthier, P., Furno, A., El Faouzi, N.-E., 2018. Road network resilience: how to identify critical links subject to day-to-day disruptions. Transp. Res. Rec. 2672 (1), 54–65. https://doi.org/10.1177/0361198118792115.

Golub, A., Martens, K., 2014. Using principles of justice to assess the modal equity of regional transportation plans. J. Transp. Geogr. 41, 10–20. https://doi.org/10.1016/j.jtrangeo.2014.07.014.

Guzman, L.A., Oviedo, D., 2018. Accessibility, affordability and equity: Assessing 'pro-poor' public transport subsidies in Bogotá. Transp. Policy 68, 37–51. https://doi.org/10.1016/j.tranpol.2018.04.012.

Halim, R.A., Kwakkel, J.H., Tavasszy, L.A., 2016. A strategic model of port-hinterland freight distribution networks. Transp. Res. Part ELogistics Transp. Rev. 95, 368–384. https://doi.org/10.1016/j.tre.2016.05.014.

Hernandez, D.O., Dávila, J.D., 2016. Transport, urban development and the peripheral poor in Colombia — Placing splintering urbanism in the context of transport networks. J. Transp. Geogr. 51, 180–192. https://doi.org/10.1016/j.jtrangeo.2016.01.003.

Holguín-Veras, J., Jaller, M., Sánchez-Díaz, I., Campbell, S., Lawson, C.T., 2014. Freight Generation and Freight Trip Generation Models. In: Tavasszy, L., de Jong, G. (Eds.), Modelling Freight Transport. Elsevier, Oxford, pp. 43–63.

Hope, C., 2008. Discount rates, equity weights and the social cost of carbon. Energy Econ. 30 (3), 1011–1019. https://doi.org/10.1016/j.eneco.2006.11.006.

Jafino, B.A., Kwakkel, J., Verbraeck, A., 2020. Transport network criticality metrics: a comparative analysis and a guideline for selection. Transp. Rev. 40 (2), 241–264. https://doi.org/10.1080/01441647.2019.1703843.

Jang, S., An, Y., Yi, C., Lee, S., 2017. Assessing the spatial equity of Seoul's public transportation using the Gini coefficient based on its accessibility. Int. J. Urban Sci. 21 (1), 91–107. https://doi.org/10.1080/12265934.2016.1235487.

Jenelius, E., 2010. User inequity implications of road network vulnerability. J. Transport Land Use 2 (3/4), 57–73.

Jenelius, E., Mattsson, L.-G., 2015. Road network vulnerability analysis: Conceptualization, implementation and application. Comput. Environ. Urban Syst. 49, 136–147. https://doi.org/10.1016/j.compenvurbsys.2014.02.003.

Jenelius, E., Petersen, T., Mattsson, L.-G., 2006. Importance and exposure in road network vulnerability analysis. Transp. Res. Part A: Policy and Practice 40 (7), 537–560.

Kaplan, S., Popoks, D., Prato, C.G., Ceder, A., 2014. Using connectivity for measuring equity in transit provision. J. Transp. Geogr. 37, 82–92. https://doi.org/10.1016/j.jtrangeo.2014.04.016.

Karner, A., Golub, A., 2019. Assessing the equity impacts of a transportation investment program. In: Lucas, K., Martens, K., Di Ciommo, F., Dupont-Kieffer, A. (Eds.), Measuring Transport Equity. Elsevier, pp. 277–290.

Kermanshah, A., Derrible, S., 2016. A geographical and multi-criteria vulnerability assessment of transportation networks against extreme earthquakes. Reliab. Eng. Syst. Saf. 153, 39–49. https://doi.org/10.1016/j.ress.2016.04.007.

Kim, H., Sultana, S., 2015. The impacts of high-speed rail extensions on accessibility and spatial equity changes in South Korea from 2004 to 2018. J. Transp. Geogr. 45, 48–61. https://doi.org/10.1016/j.jtrangeo.2015.04.007.

Klein, N., 2007. Spatial methodology for assessing distribution of transportation project impacts with environmental justice framework. Transp. Res. Rec. 2013 (1), 46–53. https://doi.org/10.3141/2013-07.

Knoop, V.L., Snelder, M., van Zuylen, H.J., Hoogendoorn, S.P., 2012. Link-level vulnerability indicators for real-world networks. Transp. Res. Part A: Policy Practice 46 (5), 843–854. https://doi.org/10.1016/j.tra.2012.02.004.

Konow, J., 2001. Fair and square: the four sides of distributive justice. J. Econ. Behav. Organ. 46 (2), 137–164. https://doi.org/10.1016/S0167-2681(01)00194-9.

Konow, J., 2003. Which is the fairest one of all? a positive analysis of justice theories. J. Econ. Literature 41 (4), 1188–1239.

Lakshmanan, T.R., 2011. The broader economic consequences of transport infrastructure investments. J. Transp. Geogr. 19 (1), 1–12. https://doi.org/10.1016/j.jtrangeo.2010.01.001.

Lee, R.J., Sener, I.N., Jones, S.N., 2017. Understanding the role of equity in active transportation planning in the United States. Transport Rev. 37 (2), 211–226. https://doi.org/10.1080/01441647.2016.1239660.

Leroux, M.-L., Ponthiere, G., 2013. Utilitarianism and unequal longevities: A remedy? Econ. Model. 30, 888–899. https://doi.org/10.1016/j.econmod.2012.10.006.

Li, F., Jia, H., Luo, Q., Li, Y., Yang, L., 2020. Identification of critical links in a large-scale road network considering the traffic flow betweenness index. e0227474 PLoS ONE 15 (4). https://doi.org/10.1371/journal.pone.0227474.

Litman, T., 2002. Evaluating transportation equity. World Transport Policy & Practice 8 (2), 50–65.

Litman, T., 2007. Developing indicators for comprehensive and sustainable transport planning. Transp. Res. Rec. 2017 (1), 10–15. https://doi.org/10.3141/2017-02.

López, E., Monzón, A., Ortega, E., Mancebo Quintana, S., 2009. Assessment of cross-border spillover effects of national transport infrastructure plans: an accessibility approach. Transport Rev. 29 (4), 515–536. https://doi.org/10.1080/01441640802627974.

Lowry, M.B., Furth, P., Hadden-Loh, T., 2016. Prioritizing new bicycle facilities to improve low-stress network connectivity. Transp. Res. Part A: Policy Practice 86, 124–140. https://doi.org/10.1016/j.tra.2016.02.003.

Luathep, P., Sumalee, A., Ho, H.W., Kurauchi, F., 2011. Large-scale road network vulnerability analysis: a sensitivity analysis based approach. Transportation 38 (5), 799–817. https://doi.org/10.1007/s11116-011-9350-0.

Lucas, K., 2012. Transport and social exclusion: Where are we now? Transp. Policy 20, 105–113. https://doi.org/10.1016/j.tranpol.2012.01.013.

Lucas, K., van Wee, B., Maat, K., 2016. A method to evaluate equitable accessibility: combining ethical theories and accessibility-based approaches. Transportation 43 (3), 473–490. https://doi.org/10.1007/s11116-015-9585-2.

Madar, G., Maoh, H., Anderson, W., 2020. Examining the robustness of the Ontario truck road network. J. Geogr. Syst. https://doi.org/10.1007/s10109-020-00320-8.

Mahmud, M., Sawada, Y., 2018. Infrastructure and well-being: employment effects of Jamuna bridge in Bangladesh. J. Dev. Effectiveness 10 (3), 327–340. https://doi.org/10.1080/19439342.2018.1483415.

Martens, K., 2006. Basing transport planning on principles of social justice. Berkeley Planning J. 19 (1).

Martens, K., 2020. How just is transportation justice theory? The issues of paternalism and production: A comment. Transp. Res. Part A: Policy Practice 133, 383–386. https://doi.org/10.1016/j.tra.2020.01.012.

Martens, K., Bastiaanssen, J., 2019. An index to measure accessibility poverty risk. In: Lucas, K., Martens, K., Di Ciommo, F., Dupont-Kieffer, A. (Eds.), Measuring Transport Equity. Elsevier, The Netherlands, pp. 39–55.

Martens, K., Bastiaanssen, J., Lucas, K., 2019. Measuring transport equity: Key components, framings and metrics. In: Lucas, K., Martens, K., Di Ciommo, F., Dupont-Kieffer, A. (Eds.), Measuring Transport Equity. Elsevier, The Netherlands, pp. 13–36.

Martens, K., Hurvitz, E., 2011. Distributive impacts of demand-based modelling. Transportmetrica 7 (3), 181–200. https://doi.org/10.1080/18128600903322333.

Merschman, E., Doustmohammadi, M., Salman, A.M., Anderson, M., 2020. Postdisaster decision framework for bridge repair prioritization to improve road network resilience. Transp. Res. Rec. 0361198120908870 https://doi.org/10.1177/0361198120908870.

Mollanejad, M., Zhang, L., 2014. Incorporating spatial equity into interurban road network design. J. Transp. Geogr. 39, 156–164. https://doi.org/10.1016/j.jtrangeo.2014.06.023.

Monzón, A., Ortega, E., López, E., 2013. Efficiency and spatial equity impacts of high-speed rail extensions in urban areas. Cities 30, 18–30. https://doi.org/10.1016/j.cities.2011.11.002.

Nahmias-Biran, B.-H., Martens, K., Shiftan, Y., 2017. Integrating equity in transportation project assessment: a philosophical exploration and its practical implications. Transport Rev. 37 (2), 192–210. https://doi.org/10.1080/01441647.2017.1276604.

Nelson, A., Lindbergh, S., Stephenson, L., Halpern, J., Arroyo, F.A., Espinet, X., González, M.C., 2019. Coupling natural hazard estimates with road network analysis to assess vulnerability and risk: case study of freetown (sierra leone). Transp. Res. Rec. 2673 (8), 11–24. https://doi.org/10.1177/0361198118822272.

Novak, D.C., Sullivan, J.F., Sentoff, K., Dowds, J., 2020. A framework to guide strategic disinvestment in roadway infrastructure considering social vulnerability. Transp. Res. Part A: Policy Practice 132, 436–451. https://doi.org/10.1016/j.tra.2019.11.021.

Ortega, E., Martín, B., Aparicio, Á., 2020. Identification of critical sections of the Spanish transport system due to climate scenarios, 102691 J. Transp. Geogr. 84. https://doi.org/10.1016/j.jtrangeo.2020.102691.

Ortuzar, J. d. D., & Willumsen, L. G. (2011a). Equilibrium and dynamic assignment. In Modelling Transport (pp. 391-427).

Ortuzar, J. d. D., & Willumsen, L. G. (2011b). Modelling transport: John Wiley & Sons.

Page, E.A., 2007. Climate change, justice and future generations. Edward Elgar Publishing, Cheltenham, United Kingdom.

Pant, R., Hall, J.W., Blainey, S.P., 2016. Vulnerability assessment framework for interdependent critical infrastructures: case-study for Great Britain's rail network. Eur. J. Transport Infrastructure Res. 16 (1), 174–194.

Papilloud, T., Röthlisberger, V., Loreti, S., Keiler, M., 2020. Flood exposure analysis of road infrastructure – Comparison of different methods at national level. Int. J. Disaster Risk Reduct. 101548 https://doi.org/10.1016/j.ijdrr.2020.101548.

Pazner, E.A., Schmeidler, D., 1978. Egalitarian equivalent allocations: a new concept of economic equity. Q. J. Econ. 92 (4), 671–687. https://doi.org/10.2307/1883182.

Pereira, R. H. M., Banister, D., Schwanen, T., & Wessel, N. (2017). Distributional effects of transport policies on inequalities in access to opportunities in Rio de Janeiro. Available at SSRN 3040844.

Pereira, R.H.M., Schwanen, T., Banister, D., 2016. Distributive justice and equity in transportation. Transport Rev. 37 (2), 170–191. https://doi.org/10.1080/01441647.2016.1257660.

Posner, R.A., 1979. Utilitarianism, economics, and legal theory. J. Legal Stud. 8 (1), 103–140.

Qi, W., Zhang, Z., Zheng, G., Lin, X., 2015. Vertex importance analysis of Xiamen road transportation networks. J. Inf. Comput. Sci. 12 (10) https://doi.org/10.12733/jics20105979.

Rawls, J., 2009. A theory of justice. Harvard University Press.

Rozenberg, J., Briceno-Garmendia, C.M., Lu, X., Bonzanigo, L., Moroz, H.E., 2017. Improving the resilience of Peru's road network to climate events. Retrieved from: The World Bank http://documents.worldbank.org/curated/en/691821490628878185/pdf/WPS8013.pdf.

Sarlas, G., Páez, A., Axhausen, K.W., 2020. Betweenness-accessibility: Estimating impacts of accessibility on networks. J. Transp. Geogr. 84, 102680 https://doi.org/10.1016/j.jtrangeo.2020.102680.

Sayers, P., Penning-Rowsell, E.C., Horritt, M., 2018. Flood vulnerability, risk, and social disadvantage: current and future patterns in the UK. Reg. Environ. Change 18 (2), 339–352. https://doi.org/10.1007/s10113-017-1252-z.

Scott, D.M., Novak, D.C., Aultman-Hall, L., Guo, F., 2006. Network Robustness Index: A new method for identifying critical links and evaluating the performance of transportation networks. J. Transp. Geogr. 14 (3), 215–227. https://doi.org/10.1016/j.jtrangeo.2005.10.003.

Shang, P., Li, R., Liu, Z., Yang, L., Wang, Y., 2018. Equity-oriented skip-stopping schedule optimization in an oversaturated urban rail transit network. Transp. Res. Part C: Emerging Technol. 89, 321–343. https://doi.org/10.1016/j.trc.2018.02.016.

Smith, G., 2009. Bangladesh Transport Policy Note. World Bank, Washington DC. Retrieved from: http://siteresources.worldbank.org/INTSARREGTOPTRANSPORT/Resources/BD-Transport-PolicyNote_9June2009.pdf.

Stanton, E.A., 2011. Negishi welfare weights in integrated assessment models: the mathematics of global inequality. Clim. Change 107 (3), 417–432. https://doi.org/10.1007/s10584-010-9967-6.

Stanton, E.A., Ackerman, F., Kartha, S., 2009. Inside the integrated assessment models: Four issues in climate economics. Climate Dev. 1 (2), 166–184. https://doi.org/10.3763/cdev.2009.0015.

Sullivan, J.L., Novak, D.C., Aultman-Hall, L., Scott, D.M., 2010. Identifying critical road segments and measuring system-wide robustness in transportation networks with isolating links: A link-based capacity-reduction approach. Transp. Res. Part A: Policy Practice 44 (5), 323–336.

Tavasszy, L.A., Ruijgrok, K., Davydenko, I., 2012. Incorporating logistics in freight transport demand models: state-of-the-art and research opportunities. Transport Rev. 32 (2), 203–219. https://doi.org/10.1080/01441647.2011.644640.

Törnblom, K.Y., Vermunt, R., 1999. An integrative perspective on social justice: distributive and procedural fairness evaluations of positive and negative outcome allocations. Social Justice Res. 12 (1), 39–64. https://doi.org/10.1023/A:1023226307252.

Van Wee, B., 2011. Transport and ethics: ethics and the evaluation of transport policies and projects. Edward Elgar Publishing.

Van Wee, B., Geurs, K., 2011. Discussing equity and social exclusion in accessibility evaluations. Eur. J. Transport Infrastructure Res. 11 (4), 350–367.

Van Wee, B., Roeser, S., 2013. Ethical theories and the cost-benefit analysis-based ex ante evaluation of transport policies and plans. Transport Rev. 33 (6), 743–760. https://doi.org/10.1080/01441647.2013.854281.

Vanoutrive, T., Cooper, E., 2019. How just is transportation justice theory? The issues of paternalism and production. Transp. Res. Part A: Policy Practice 122, 112–119. https://doi.org/10.1016/j.tra.2019.02.009.

Velaga, N.R., Beecroft, M., Nelson, J.D., Corsar, D., Edwards, P., 2012. Transport poverty meets the digital divide: accessibility and connectivity in rural communities. J. Transport Geography, 21, 102-112. doi:j.jtrangeo.2011.12.005.

Volgers, M., Nagel, G., de Jong, W., Kluskens, R., 2016. Inland waterway navigability improvement feasibility study: Early assessment & initial prioritization report. Royal Haskoning DHV, Amersfoort.

Welch, T.F., Mishra, S., 2013. A measure of equity for public transit connectivity. J. Transp. Geogr. 33, 29–41. https://doi.org/10.1016/j.jtrangeo.2013.09.007.

Yap, M.D., van Oort, N., van Nes, R., van Arem, B., 2018. Identification and quantification of link vulnerability in multi-level public transport networks: a passenger perspective. Transportation 45 (4), 1161–1180. https://doi.org/10.1007/s11116-018-9892-5.

Yu, N., de Jong, M., Storm, S., Mi, J., 2013. Spatial spillover effects of transport infrastructure: evidence from Chinese regions. J. Transp. Geogr. 28, 56–66. https://doi.org/10.1016/j.jtrangeo.2012.10.009.

Yu, N., de Roo, G., de Jong, M., Storm, S., 2016. Does the expansion of a motorway network lead to economic agglomeration? Evidence from China. Transp. Policy 45, 218–227. https://doi.org/10.1016/j.tranpol.2015.03.014.

Zhao, P., Howden-Chapman, P., 2010. Social inequalities in mobility: the impact of the hukou system on migrants' job accessibility and commuting costs in Beijing. Int. Dev. Planning Rev. 32 (3/4), 363.

Zhu, Y.-J., Hu, Y., Collins, J.M., 2020. Estimating road network accessibility during a hurricane evacuation: A case study of hurricane Irma in Florida. Transp. Res. Part D: Transport Environ. 102334 https://doi.org/10.1016/j.trd.2020.102334.