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Including equity considerations in resilient transport network planning and analysis: A flood impact perspective

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Abstract

Transportation plays a pivotal role in society in the accessibility of socio-economic functions, such as education and health services. At the same time these transport networks are put under pressure due to increasing demands and the often-increasing occurrence of climate-induced events. To increase resilience of the transportation network to disruptions, network criticality has been used to prioritise segments of the network for interventions. Here we present how equity principles can be applied in the context of decision making for resilient infrastructure. This is done for both a data-rich (The Hague, The Netherlands) and data-poor (Pontianak, Indonesia) environment. The results show that depending on the underlying equity principle different intervention locations are prioritized and changes the impact for different socio-economic groups and the general population.

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Keywords: resilience; network criticality; climate change adaptation; social vulnerability; equity;

1. Overview and motivation

Transportation systems are being put under increasing pressure due to socio-economic developments and increased transportation demand. This increases even more when considering other factors such as disruption of the transportation system due to intensifying climate change and climate-induced hazards, such as increasing extreme precipitation events. Transportation studies rely on network theory (Lin & Ban, 2013), which opened up analyses on accessibility (Wang et al., 2009) and impact assessment of natural hazards to transport networks (Espinet & Rozenberg, 2018). This enables transport authorities to prioritise interventions yielding maximum benefits to the users

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of the road. Here, we present research that builds upon these analyses by taking into account equity considerations in the prioritisation of investment within resilient transport planning and analyses.

Transport infrastructure plays a pivotal role in the accessibility of socio-economic opportunities, for example employment, education, and healthcare services. Accessibility to these opportunities is essential for all individuals regardless of their societal background (Geurs & Van Wee, 2004). Although policies in the past have aimed to reduce the inequalities related to accessibility (Handy, 2020; Jafino et al., 2020; Jenelius & Mattsson, 2015; Martens et al., 2012,2019) studies show that the groups with lower societal status in society do not equally benefit from new or improved transport infrastructures and services (Van de Walle & Mu, 2011), while at the same time being more exposed and vulnerable to disruptions of transport services (Kilgariff et al., 2019). In this study, we propose an approach on the adoption of multiple equity principles, drawn from theories of distributive justice, to support climate-resilient transport network planning and analyses.

2. Methodology

In this study, we demonstrate the effects of different equity principles applied in the context of decision making for resilient infrastructure. The methodology used in this study builds upon the approach as described in Jafino (2021), and is extended with steps to include interruption due to flooding events. Our approach consists of 4 general steps (shown in Fig. 1): 1. The identification of socially vulnerable groups (optional in data-scarce environments) 2. Creation of trips based on network, origins and destinations 3. Assessment of criticality of each segment in the network with and without introduction 4. Prioritisation making use of equity principles. We demonstrate the different steps of this methodology based one experiences in two case studies making use of flood extent scenarios and making use of open-access socio-economic data.

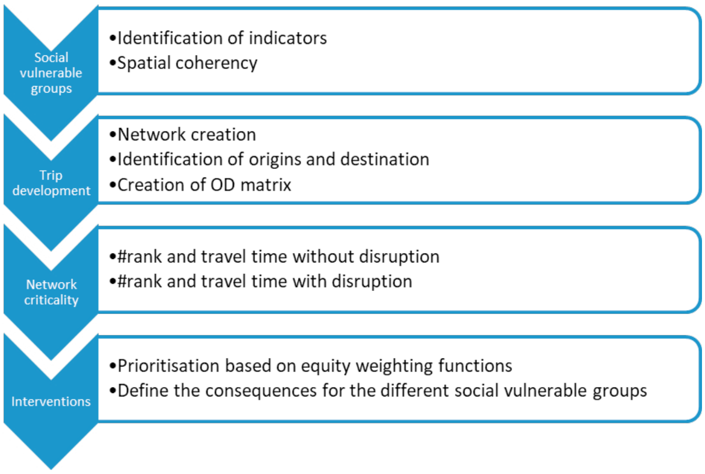

Fig. 1. Overview of the general approach to include equity principles in transport infrastructure.

2.1. RA2CE modelling framework

Here we make use of the RA2CE platform - Resilience Assessment and Adaptation for Critical infrastructurE – to demonstrate the way equity principles can be used. RA2CE is developed to support infrastructure owners and operators in resilience assessments and adaptation decision-making and produces resilience maps for infrastructure networks. This can be expressed in terms of annual expected damage for operator costs (direct) and annual expected losses for road users for societal costs (indirect) for identification of hot spots (Espinet & Rozenberg, 2018), both of which could support resilient infrastructure planning. The network analyses are based on graph theory which have been used widely in logistics studies. One of the basic functionalities is network criticality which identifies the most critical segments in a network. Critical segments are those that have a high consequence of failure irrespective of the likelihood of failure (Murray et al, 2008, Kaplan and Garrik, 1981). For the quantification of network performance, a redundancy-based approach is a common method to analyse the impact of the disruption of single links to the undisrupted network (Sullivan et al., 2010).

2.2. Identification of socially vulnerable groups in accessibility analyses

Based on existing literature, several different social vulnerability indicators during a disruption have been identified. The most used indicators are wealth, household composition, age, and ethnicity at a household level (Cutter et al., 2003; Fekete, 2009). For example, more wealth results in better chances to prepare and recover from events. The household composition could influence the means. For example, single-parent households have in general fewer means which could potentially influence resilience to disruption (Koks et al., 2015). Age is accounted for where in general families with children below 12 years and households with a relatively high percentage of 65 years old people are considered as more vulnerable (Cutter et al., 2003; Hewitt, 2014). For example, households with young children can be affected differently during a flood event when accessibility to schools and/or day care is affected. On the other hand, elderly people could be affected due to decreased possibilities in mobility. Ethnicity could possibly influence social vulnerability due to for example language and cultural barriers (Fothergill et al., 1999).

Table 1. Overview of the equity principles used in this study.

Distributive principles for criticality analysis	Description	Implementation in criticality analysis	Implementation in prioritization of interventions
Utilitarian	Maximizes utility or benefits for all	Use the actual transport demand for each Origin-Destination (OD) pair, so that the aggregated serviceability is maximized	Prioritise the interventions towards the road segments that experience the largeste consequences (delay * number of users)
Egalitarian	Equal accessibility for each socio-economic/spatial group	Each OD pair counts as 1, to ensure that each OD pair is equally important	The number interventions are distributed equally over the different socio-economic groups and within these groups prioritized to the locations with the largest consequence for each socio-economic group (travel delay * number of users)
Prioritarian	Prioritize the more socially vulnerable group	Equity-weight the traffic, with higher weights given to the transport demand of poorer subdistricts	Higher priority is given to the subdistricts that without disruption already experience the largest travel distance to key facilities

2.3. Equity principles

Three different equity principles (utilitarian, egalitarian, and prioritarian; see Table 1) have been applied in the two different case studies to identify (i) how different socially vulnerable groups are affected by climate-induced disruption of the system and (ii) how prioritization of important road segments change when looked from different viewpoints. To perform the analyses the traffic criticality module of RA2CE is used in combination with a set of socio-economic destinations (e.g. health care) for the different equity principles.

2.4. Two case-studies

We evaluate the effects of including different equity principles in two case studies:

1. Prioritization of flood resilience investments in The Hague, The Netherlands. Such investments are aimed at maintaining the serviceability of the transport system in times of flooding, where resilience in this study is

proxied by the decrease in travel time[1]. The prioritization is carried such that it yields maximum benefits to the transport users and to society. We operationalize the three different equity principles to evaluate the benefits of the interventions, where some of the principles explicitly account for the distributional impacts of flooding and distributional benefits of resilience investments. To this end, using disaggregated census data, we first cluster the neighborhoods in The Hague based on their socioeconomic status, and then evaluate the impacts of flooding to each socioeconomic group's accessibility to key facilities in the city. This case study thus serves as an example of applying equity principles in a data-rich environment (Lourens, 2021).

2. Identification of critical road segments in Pontianak, Indonesia. Criticality analysis aims at prioritizing road segments in the transport network based on their importance on the functionality of the transport system (Jafino et al, 2020). This case study is in principle similar to the previous case study. However, in the absence of flood maps, here we focus on the criticality of the road segments under a no-disruption scenario. The contribution of this case study is in showing how we can still perform equity-based transport network analysis in the absence of sufficient socio-economic data. Hence, the neighborhoods are not clustered based on their socioeconomic status, but rather solely based on their locations. This case study thus serves as an example of applying equity principles in a data-scarce environment.

3. Results

3.1. Case study The Hague

When working in a data-rich environment, such as The Hague, the Netherlands, socio-economic groups can be clustered at neighborhood level based on publicly available data by the national center of statistics (CBS) on age, household composition, ethnicity, and income. Based on density-based spatial clustering of applications with noise (DBSCAN) and validation by poverty indices of the municipality The Hague seven distinct socio-economic groups could be distinguished (Fig. 2-a). Road were assumed to be disrupted when the flood depth was larger than 0.3 m (Pregnolato et al, 2017, Fig. 2-b).

(a) (b)

Fig. 2. (a) Result of the spatial clustering based on DBSCAN; (b) Water depth based on an extreme precipitation event (70 mm for 1 h) (Climate Atlas Municipality of The Hague)

The flood impact for different socio-economic groups was assessed by assessing the relative increase in travel time to key facilities due to the floods. This is determined as the percentual increase in travel time compared to the business-as-usual situation without disruption and a basic functionality in the RA2CE modelling framework. Key facilities

[1] Ideally, resilience should be proxied by not only the decrease in travel time during the disruption, but also by how fast the system gets back to its initial service level before the disruption.

were separated in three levels of importance, similar to the categories in Maslow's Hierarchy of Needs. Physiological needs include health care and pharmacies, safety and security needs include education, daycare, banks, and social needs include locations for leisure including bars, restaurants and community spaces. Based on the relative increase in travel time due to the floods this demonstrates that the socio-economic group described by lower educated, less wealthy people with a foreign ethnic background (Fig. 3-top, light blue) experience the largest effects (with an increase varying from 100% - 150%) compared to the normal situation. This socio-economic group can be considered as the most vulnerable, based on previous studies on social vulnerability (Cutter et al., 2012). On the other hand, the socio-economic group described by wealthy elderly inhabitants (Fig. 3-top, red) experiences the least relative increase in travel time (varying from 10% - 20%).

Besides the increased travel times, people that are completely blocked from their destinations should also be considered (Fig. 3-bottom). Also, here the lower educated, less wealthy group with a foreign ethnic background is most affected with 69% more people affected compared to all other groups. This is partly related to their geographical location in the city center, where many roads were blocked due to the rainfall event.

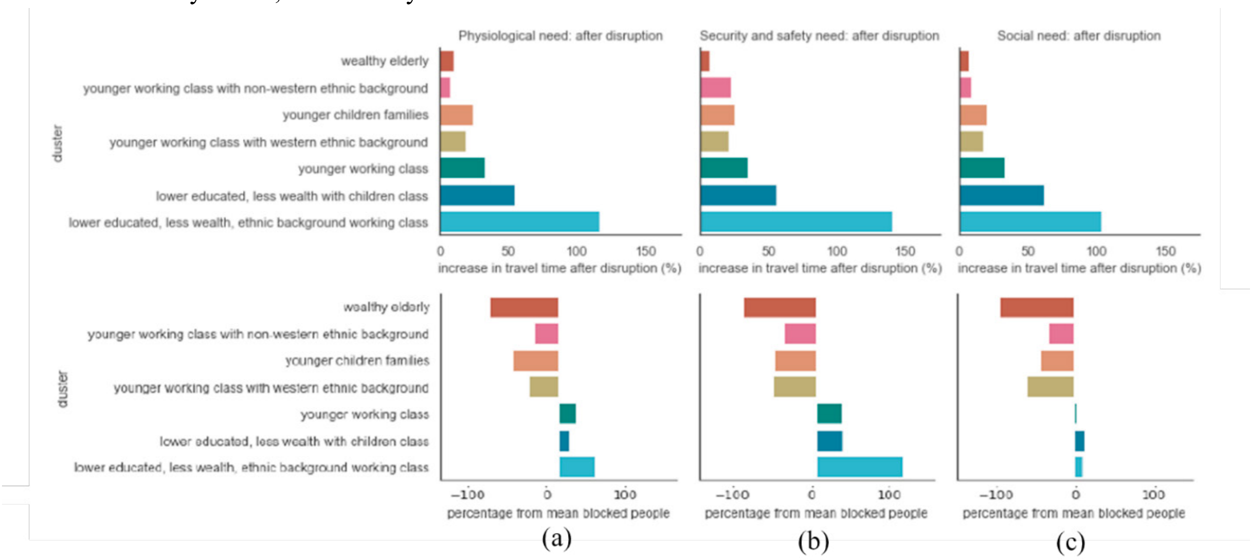

Fig. 3. Relative increase in travel time compared to the normal situation (top) and relative % of people that could not make their trip anymore and were blocked (bottom) for the different socio-economic groups. This is expressed for 3 different types of destinations related to (a) Physiological needs (e.g. health care) (b) Security and safety needs (e.g. schools daycare) (c) Social needs (e.g. leisure, bars, restaurants).

Fig. 4 demonstrates the prioritized locations identified to place interventions. Different road segments were selected to improve segments susceptible for flooding. Making use of the information on the different socio-economic groups it is possible to use the three different equity principles and thus distribute the interventions selectively with regards to the benefit of the specific societal groups. When making use of the Utilitarian principle the interventions are prioritised to locations where most people travel and where most destinations are located, which in our situation is based in the city centre. When making use of the Rawls' Theory of Justice, the locations are selected as such that the neighbourhoods considered as the most vulnerable benefit most. These locations are mostly located East of the city centre. The Equal Sharing principle prioritises the interventions as such that each societal group benefits equally. As the different societal groups are also located in different areas of The Hague, using the Equal Sharing principle leads to the placement of interventions to be scattered throughout the network. Some locations (mostly in the city centre) are prioritized in all three of the equity principles, which can be seen as no-regret interventions since they provide substantial benefits based on any of the three principles of justice.

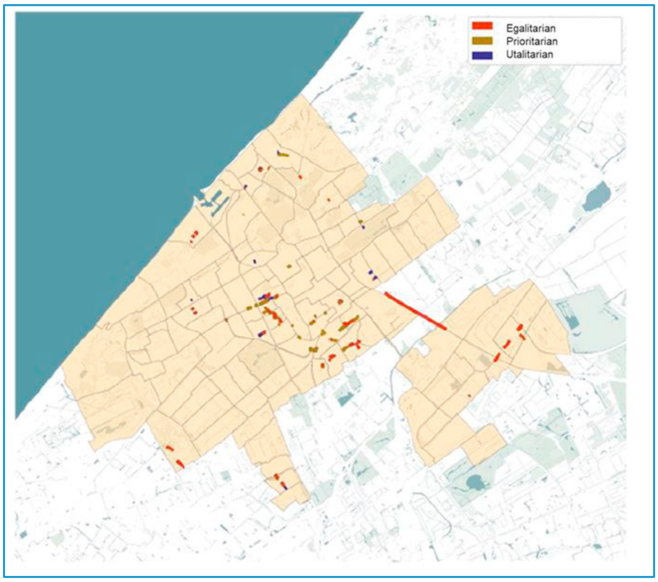

Fig. 4. *Selected road segments for intervention based on different equity principles*

3.2. Limited socio-economic data. Pontianak case-study.

In the absence of sufficient socio-economic data, equity-based transport network analysis can still be conducted. We demonstrate this for identifying critical links in Pontianak, Indonesia, where no local socio-economic statistics are used to perform the equity-based analysis. In this case, we define the criticality of a link (i.e., road segment) as its contribution to providing access to healthcare services (see Fig. 5). We performed criticality analysis based on two principles: the utilitarian principle – which is a default principle implicitly adapted in criticality analysis studies – and the egalitarian principle (Jafino, 2021). Since there are no socio-economic statistics, identification of socially vulnerable groups is not possible and hence we exclude the prioritarian principle.

(a) (b) (c)

Fig 5: Pontianak criticality analysis model setup: (a) population hotspots from WorldPop as origins of transport demand, (b) healthcare facilities as destinations of transport demand, (c) the main road transport network.

Criticality analysis results in ranking of the road segments, with more important and critical roads having higher ranks. We calculate the criticality ranking of all roads in Fig 5-c based on both the utilitarian and the egalitarian principles, and then compare the resulting rankings of each road segments based on the two principles. Fig. 6 shows the results of this comparison.

Fig. 6. Difference in criticality rankings between the egalitarian and the utilitarian principles. Negative values imply that the road segment is more critical from the egalitarian perspective (e.g., it ranks 2nd based on the egalitarian but ranks 8th in the utilitarian principle), vice versa.

The first important observation is that there are no road segments which criticality ranking stays the same between the two principles. Most road segments in the northern part of the city become more critical when viewed from the egalitarian principle. On the other hand, many road segments at the center of the city are more critical from the utilitarian principle, but less important based on the egalitarian principle. This can be explained by the fact that there are more people living around the center of the city (Fig. 5), making road segments in that area critical from a utilitarian perspective. Conversely, there are only few people living in the northern part of the city, making the road segments in that northern part unimportant from a utilitarian view. The results indicate that by focusing only on a utilitarian viewpoint, we would focus our investment only on road segments at the center of the city, while disregarding the road segments connecting the less densely populated area at the north of the city.

4. Conclusion and future works

This research compares how equity principles affect transport criticality and how the locations of interventions can be prioritized based on the different principles. To reduce accessibility inequalities, we urge transport authorities and researchers to critically determine the aim of their interventions (e.g., maximizing overall accessibility or improving the accessibility of worse-off people), and based on that, perform a criticality analysis based on either of the different equity principles. We also demonstrate here the use of publicly available global data, which shows that also in data-scarce environments equity principles can be applied and may support the prioritisation of locations for interventions. Future works and recommendations include a standardised approach to adopt equity principles in decision making, resulting in better-informed decision making within climate resilient transport planning. Another avenue could be spatial identification of vulnerable groups using open data, to enable better equity analyses in data-scarce areas.

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