

Article

Development of an Index of Transport-User Vulnerability, and its Application in Enschede, The Netherlands

Kain Glensor 

Wuppertal Institute for Climate, Environment and Energy gGmbH, 10178 Berlin, Germany;
kain.glensor@wupperinst.org

Received: 22 March 2018; Accepted: 6 July 2018; Published: 9 July 2018



Abstract: An index of accessibility-based vulnerability is created based on a definition of transport-user vulnerability regarding transport accessibility created for the EMPOWER project, in order to assess the project's key performance indicator of the inclusion of vulnerable people in the project's scheme. The objective of the index is to account for various individual vulnerability aspects, but also for the 'multi-dimensionality' of vulnerability, i.e. individuals may be vulnerable because of one specific aspect (e.g., disability), or they may be vulnerable because of multiple aspects which, if assessed in isolation, wouldn't classify the individual as vulnerable. Users of the project scheme in the Dutch city of Enschede are surveyed on, inter alia, their vulnerability based on this definition, according to their income, mobility budget, physical mobility, age, gender, living situation, nation of birth, and education. According to individual questions, 1% to 54% (single parents and females, respectively) of respondents have some level of vulnerability. According to the index, 23–36% of respondents can be considered to be vulnerable. Suitably modified for local conditions, the index is relevant to cities, especially quickly developing cities where congestion reduction is or has been a priority, insofar as it offers a way of measuring and monitoring the vulnerability of the users of their transport system. Finally, steps to adapt the index to other settings (cities or countries) are discussed.

Keywords: transport; vulnerability; accessibility

1. Introduction

The EMPOWER project has a key performance indicator (KPI) related to the project's inclusion of vulnerable users. To assess this, various perspectives of road-user vulnerability are explored, culminating in a methodology to define and calculate the vulnerability of individual transport users (the vulnerability index) based on a survey of a subset of users carried out in the city of Enschede, the Netherlands. The objective of the index is to assess the overall vulnerability of the survey respondents, but also to account for 'marginal' responses to the questions. The initial intention of the index is to assess the project KPI, and it was co-developed as part of the process of evaluating this KPI. However, the underlying idea of an index of accessibility-based vulnerability is considered to be applicable and relevant in other cities; the required modifications from the example are discussed in the discussions section.

1.1. EMPOWER Project

EMPOWER is a European Commission Horizon 2020 project researching the encouragement of people to reduce their use of (fossil-fueled) cars through positive incentives, such as information, points, discounts, rewards, community support, and games, rather than charging, pricing, rationing, restrictions and regulation. EMPOWER applies various approaches in 'Living Labs' in 12 cities or

regions throughout Europe. The Dutch city of Enschede is one of EMPOWER's 'Living Lab' cities, in which the 'SMART' app is being used (<https://www.smartintwente.nl/>) to encourage cycling, walking, and public transport use by providing points (redeemable at local stores) when those modes are used.

The project has four key performance indicators (KPIs) involving users' transport behavioral change, changes in users' perception of accessibility and attractiveness, user satisfaction with the service, and, of most interest to this paper, vulnerable travel groups, from which the project has promised to attain a "10% response rate". The author is primarily responsible for the definition of vulnerability applied in the project, and for assessing the results of project activities according to the project's KPIs, but had only an indirect influence on the questionnaire provided to a subset of users in the Enschede Living Lab on which the analysis presented in this paper is based.

1.2. Definitions of Vulnerability

According to the Oxford dictionary, vulnerability means "the quality or state of being exposed to the possibility of being attacked or harmed, either physically or emotionally." [1] In a climate change-specific sense, according to Younus and Harvey, regarding definitions of vulnerability, "most are considered to be in the 'system' and based on the system's sensitivity and susceptibility. Others are related to potential loss of property and lives, though these are also within the system". [2]. Specifically related to transport policies, vulnerability can be split into two types: firstly (and more commonly), a definition based on health and safety aspects of transport activities, and secondly, one based on social aspects, which is closely related to the idea of accessibility: [3] "The accessibility of an activity for a person is the ease with which the person can get to places where that activity (e.g., education, work, leisure) takes place. The term accessibility therefore refers to the ability to reach activities and not movement itself using different modes of transport."

1.2.1. Health and Safety Definition

Vulnerability, defined in terms of health and safety, revolves around transport-users' ability to avoid crashes, and/or their susceptibility to injuries resulting from crashes. Pedestrians, cyclists, and motorized two-wheelers are commonly included in lists of vulnerable transport users according to this reasoning [4–7]. Eisses [8] listed three aspects that contribute to this type of vulnerability:

1. Physical vulnerability stemming from the lack of a protective 'cage'.
2. Physical vulnerability stemming from (relative) frailty, especially in an accident, e.g., the elderly and children.
3. Behavioral vulnerability stemming from a person's (relative) inability to safely participate in the transport network in a specific transport mode, e.g., people with limited experience, such as children, the elderly, and people with little driving experience.

The OECD [6] mirrors the logic of vulnerability being strongly affected by the protection offered by a car, defining vulnerable road users as "those most at risk in traffic ... mainly those unprotected by an outside shield, namely pedestrians and two-wheelers, as they sustain a greater risk of injury in any collision against a vehicle and are therefore highly in need of protection against such collisions". They further define the elderly, the disabled, and children as especially vulnerable groups.

1.2.2. Social Definition

The social definition of (transport) vulnerability is closely related to the concept of accessibility, i.e. "the ease in meeting one's needs in locations distributed over space for a subject located in a given area" [9]. Accessibility depends on:

- The socio-economic characteristics of the user in question,

- The quality and quantity of the places that the subject wishes to visit, such as workplaces, schools or shops/supermarkets, and where those places are relative to each other and the subject's dwelling, and
- The number of modes available to the subject to reach those locations and their relative quality.

Note that mobility and accessibility are related, but separate concepts. Accessibility can be attained through proximity, i.e. living close to services, and/or by mobility, i.e. having better (faster, more frequent, easier, etc.) transport options to reach those services. There is a significant correlation between increased wealth and increased accessibility as, as wealthier people will tend to enjoy advantages in both proximity and mobility, as they can afford to live close(r) to their destinations, while "lower-income groups (and vulnerable groups in general) [have less accessibility] due to high/inequitable transport fares, a lack of public transport provision to areas where low-income populations live, and a lack of safe and high quality infrastructure for these users (including sidewalks, which are often neglected in favour of roads)" [4]. Furthermore, wealthier people can afford (extra) travel in order to reach their destinations.

Sandt [10] listed the groups that can be considered vulnerable "traditionally underserved populations—sometimes referenced as at-risk, vulnerable, low-resource, or disadvantaged" according to the United States (US) Federal Highway Administration's definition:

- Low income
- Minority
- Older adults
- Limited English Proficiency (LEP)
- Person(s) with disabilities

1.3. Other Relevant Aspects to a Transport-Specific Vulnerability Index

1.3.1. Multi-Dimensionality

The factors contributing to transport vulnerability are varied, and interact and combine to affect any individual's vulnerability. An individual may have characteristics that, when examined in isolation, do not qualify them as especially vulnerable. However, when examined as a whole, that same individual may be vulnerable due to the interaction and combination of multiple (perhaps non-severe) characteristics. Cessato (2017) [11] raised the issue of the "intersectionality" (multi-dimensionality) of transport vulnerability, particularly in relation to women's vulnerability "... fear and victimisation are not only about age or gender but [are] rather a result of the intersection of a set of individual's characteristics. Being a disabled and poor individual creates 'synergic layers of disadvantage' that affect how one perceives and experiences the world and expresses fear".

Similarly, for the issues related to accessibility, poverty, transport poverty, fuel poverty, and transport disadvantage, the UNDP [12] and SUSTRANS [13], Dodson and Sipe [14], Pyrialakou et al. [15], and Xiao et al. [16] have developed indices accounting for the multi-dimensionality of the respective issues. However, none of these include the user-level examination of vulnerability related to accessibility.

1.3.2. Social Aspects of Transport

Transport is mostly not a means in its own right, but rather the tool used by people to access social interactions, education, services, and employment. As such, the transport system interacts with the social fabric of cities and communities. This has given rise to analyses of the transport system through the lens of social aspects and accessibility, especially related to poverty and transport/fuel poverty [17,18] or transport disadvantage [15,16,19], and social exclusion stemming from their transport options [20]. Considering 'urban justice' is a further way of examining the social aspects of the transport system, as it "frames urban transportation as an issue of justice: contemporary transport systems are characterized by injustice, as they tend to favour and prioritize motorized transport, accepting that

considerable environmental and social burdens are put on more sustainable forms of transportation, other traffic participants, and society as a whole" [21].

2. Vulnerability as Applied in the EMPOWER Project

If the modal definition, as described above, were applied to assess the project's inclusion of vulnerable people, the project would be—in the case of cycling and walking—effectively encouraging people to become more vulnerable. As this was not the intention of the KPI, the social/accessibility definition was applied to assess the vulnerable groups' KPI. Accordingly, the following definition of vulnerability was developed for the EMPOWER project.

"Social groups which are disadvantaged in the transport system in general. Generally, this will mean people outside the group of physically and intellectually fit and able employed adults traveling to and from a single workplace on weekdays" (internal documentation). Practically, the definition is considered to include the following groups:

- Low-income groups
- Children, youths, and the people caring for them
- Women
- The elderly
- People with disabilities
- Lower education people
- Non-locally born people

Application in the Enschede Living Lab

In order to assess the performance of the scheme, via the project's KPIs, a questionnaire was distributed in April and May 2017 amongst a subset of SMART users who had participated in a particular campaign. The users were self-selected from several local companies and the faculty and students of the local university, and from them, the participants in the survey were also self-selected. This is appropriate, as the primary purpose of the survey was to establish the vulnerability and other aspects of the participants of the scheme itself, not to compare them to the wider population. Only particular transport behavior was rewarded in the scheme; participation in the scheme or the survey was not, so the length, detail, and number of questions was kept to a minimum in order to maximize the number of responses. Of the ≈ 650 participants in the scheme, 191 survey responses were received.

The questionnaire contained, inter alia, the eight accessibility-related vulnerability questions as contained in Table 1. The questions included in the survey were influenced by the vulnerability definition described above and the author, but responsibility for the survey rests with the Living Lab organizer.

In order to account for each of the aspects included in the survey, the spectrum of possible responses to each question, and particularly the multi-dimensionality of the underlying vulnerability, an index is developed to incorporate these aspects, as described below.

3. Vulnerability Index

In order to adequately assess whether the project's KPI was met for the responses to the survey described above, an index was developed that also accounts for the various responses to the questions posed (including their severity) and the multi-dimensionality of vulnerability represented by the questions. No other example could be found of an equivalent index of personal vulnerability in accessibility terms. While the sources described in the introduction list the aspects that affect individuals' vulnerability, none of them attempt to combine them into a single index, or describe the relative severity of the aspects.

Arguably, six of the eight factors that were chosen as indicators for vulnerability are income-related: these are either literally income, proxies for income (mobility budget), or factors with a correlation with income (education, age, gender). The author argues that this is acceptable, as each of the factors is relevant for aspects other than its relation to income, and moreover, because of the correlation between income/wealth and accessibility.

Each of the responses to relevant questions was allocated 0–5 points according to the severity of the vulnerability represented by the response, with five points representing the maximum. Income below the ‘poverty line’ and physical limitations (i.e. disability) were used as a reference mark for vulnerability, even in isolation (five points), with the points for other responses based on those conditions according to the author’s judgment based on the literature quoted in the introduction discussing vulnerability and the causes for it. The ‘poverty line’ was applied as per the definition of the Netherlands Institute for Social Research, and is set at €1,063 for a single person [22]; corresponding to €1,220 before tax [23]. Additionally, below-median incomes were also allocated points; these are defined by the median disposable income for the Netherlands according to the OECD [24]: €25,000pa; corresponding to €2,846 gross per month [23]. As such, responses of gross monthly income <€999 (\approx poverty) were allocated five points, €2–3000 (\approx below median) was allocated one point, and €1–2000 was allocated three points.

The possible responses to the questions are partly qualitative and subjective (e.g., mobility budget, physical limitations), and so do not allow more precise allocation methods, or are not sufficiently detailed to address the actual source or magnitude of vulnerability. For example, being responsible for children’s mobility is a source of vulnerability; this is only weakly captured by whether someone is single or in a couple with children, and ignores the *number* of children that person is responsible for (if any, the other partner may be responsible for the children’s mobility). Similarly, individual income is asked, but average income across the household would be a more useful measure for judging poverty. As such, the mostly qualitative allocation of points is the best available method, and regardless, an extensive study of the magnitude of vulnerability of each response would be beyond the available resources.

Each respondent’s overall vulnerability was determined by the total of the points corresponding to their responses. For the purposes of the KPI assessment, a respondent is considered to be vulnerable with an aggregate of five points or more. Since applying such a threshold is contrary to the idea underlying the vulnerability index that vulnerability is a spectrum rather than a yes–no proposition, but is required in order to be able to assess the KPI, the proportions of responses for four and six points or more were also calculated.

Table 1. Vulnerability-related questions in the Enschede questionnaire with the possible answers and corresponding vulnerability points.

Questions	Vulnerability Aspect Considered	Possible Answers	Vuln. Points
All questions could be left blank and had a “rather not say” option, which is not listed here for brevity			
How would you describe your mobility budget?	Transport poverty	Ample: It does not play a role in the choice of my transport mode	
		Tight: It affects the choice of my mode of transport	2
		Very tight: It makes me choose the cheapest mode of transport	4
Do you have some physical limitations that make it difficult for you to cycle or walk properly?	Physical mobility	Yes	5
		No	
What is your gender?	Safety from assaults/harassment	Female	2
		Male	

Table 1. Cont.

Questions	Vulnerability Aspect Considered	Possible Answers	Vuln. Points
What is your age?	Diminished mobility with age	19–54	
		55–64	1
		65–74	3
		>75	5
What is your country of birth?	Language proficiency	Open	1 for non-NL
What is the highest education diploma you have obtained?	Social disadvantage	None	4
		Secondary	3
		Vocational/trade school	2
		University	
What is your current living situation?	Additional transport difficulties with children	Single	
		Single with children	3
		I live with parents/relatives	
		I live with friends/housemates	
		Couple with children	1
What is your gross monthly income?	Poverty	Couple without children	
		<€999	5
		€1–2000	3
		€2–3000	1
		€3–4000	
		>€4000	

4. Results

The following section contains the results of the analysis of the survey carried out in Enschede, as it pertains to the vulnerability of the respondents. Additionally, the results of questions about perceived accessibility and user satisfaction compared with the respondents' vulnerability are included.

Table 2 shows the results of the vulnerability-related questions in the Enschede questionnaire. If the various vulnerability-related questions are considered in isolation, the questionnaire has a response rate from vulnerable people of 1% to 54%.

Table 2. Responses to individual vulnerability-related questions from Enschede questionnaire (N = 191, blank responses excluded for percentages).

Topic	Response	Vulnerability Points	% Responses
Mobility budget	Comfortable		68%
	Tight	2	25%
	Very tight	4	7%
Physical limitations	No		93%
	Yes	5	7%
Gender	Male		46%
	Female	2	54%
Age	Non-vulnerable responses		90%
	55–64	1	10%
Highest qualification	Non-vulnerable responses		88%
	Vocational/trade	2	6%
	Secondary	3	7%
Living situation	Non-vulnerable responses		56%
	Couple with children	2	43%
	Single with children	4	1%
Gross monthly income	Non-vulnerable responses		48%
	€2–3000	1	27%
	€1–2000	3	12%
	<€999	5	13%
Native country	Non-NL	1	6%
	Netherlands		94%

As shown in Table 3, if the vulnerability index is applied and five points was used as the threshold, the questionnaire obtained a response rate of 30% of vulnerable people. For thresholds of vulnerability ≥ 4 or ≥ 6 , the response rates were 36% and 23% respectively. An alternative way of examining these results in relation to the level at which the threshold could be set to meet the 10% KPI, which is nine points in this case.

Table 3. Vulnerability according to the vulnerability index.

Vulnerability	% Responses
4 points or more	36%
5 points or more	30%
6 points or more	23%

Figure 1 shows the distribution of respondents according to their vulnerability score, with the majority of responses at relatively low vulnerabilities (0–3), tailing off at higher vulnerabilities, as expected.

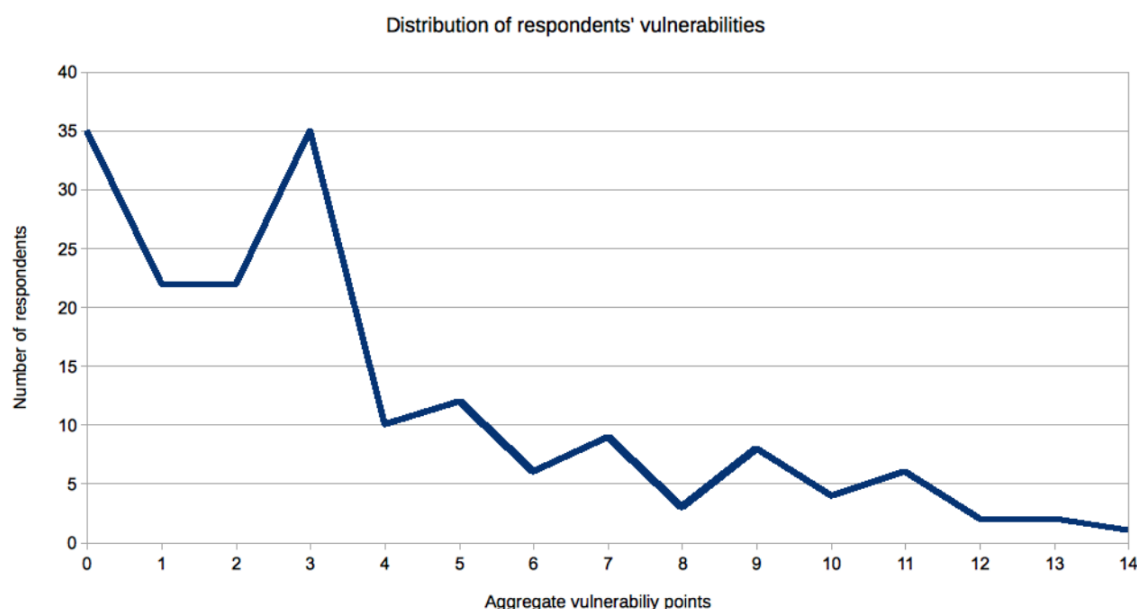


Figure 1. Graph of distribution of vulnerability scores.

5. Discussion

5.1. Enschede Results and Index Development

The index, as applied, is effective in its primary task of unifying the assessment of inclusion of vulnerable people in the scheme studied, while including aspects and responses that would be ignored or over/understated, or ignored outright, by an analysis of a proportion of respondents above or below a threshold set for each aspect. In isolation, the Enschede survey has affirmative responses to the various vulnerability-related questions of 1% to 54% (single parents and females, respectively). In contrast, the index of vulnerability resulted in an overall vulnerability of 30% with a threshold for vulnerability of five points, or 36% or 23% if a threshold of four or six points is applied, respectively.

The 54% response rate for females provides a good example of the added utility of the vulnerability index, namely that it address the 'multi-dimensionality' of vulnerability. As females are not automatically or intrinsically especially vulnerable (in the sense that a disabled person could be considered vulnerable), it would be disingenuous to claim a response of vulnerable groups of 54% in a general sense based on this result. However, female gender is factor that can increase an individual's vulnerability in certain

situations, locations, or in the presence of other personal factors. The same logic applies for all other non-definite/definite vulnerable/not-vulnerable responses.

In the example application of the index presented in this paper, the process of indicator selection and weighting was limited by needing to be based on an external survey, and by limited resources precluding a more in-depth or multi-user (indicator selection and) weighting process. Similarly, aspects considered in the survey cover an adequate range of accessibility-related vulnerability, although they could be improved by being more specific to the sources of vulnerability. This is partially due to the questions predating the development of the index and the lessons learned developing it. The sample group used for the analysis detailed in this paper is by design a survey of a scheme drawn from the staff and students of a university and local companies' staff, which is not representative of the population. However, the index is initially developed to assess the project's KPI on vulnerable groups, which pertains to users of the scheme and is expressed in absolute, rather than relative, terms. Thus, in this specific application, the index can be said to be valid if the reader (broadly) agrees with the points allocation, and the underlying process of calculating the index. The inverse result of nine points as the necessary threshold for the 10% KPI adds validity (regarding meeting the KPI, the relevance of which beyond the project is questionable), insofar as it would allow for significant error in the methodology and still meet the KPI.

In general, the reliability/validity of the index relies on several factors. Firstly, there is the presumption that such a complex idea as vulnerability can be reduced to a single figure. Secondly, there is reliance on the points allocation being an accurate or at least fair representation of accessibility-related vulnerability in the location of interest. Any contentious allocations could be subject to a sensitivity analysis. The third determinant of the index's reliability/validity is the quality of the survey sampling.

For further applications of the index, a more robust methodology for indicator selection and weighting should be applied, if possible. Ideally, the indicators would be established quantitatively, establishing which aspects determine vulnerability locally, and allocating points to the various conditions within each aspect and ensuring that the points allocated are representative within the aspects, but also across the aspects quantitatively or as quantitatively as possible. Alternatively, the process could be completed qualitatively/subjectively based on (local) experts' judgment, either individually or collectively. Quantitative/objective allocation would require a large amount and wide range of data, and each part is associated with methodological difficulties. Castillo and Pitfield [25] provided a useful methodology for a more in-depth process of indicator selection and weighting. Also, questions directly addressing the causes of vulnerability should be asked, and attention ought to be paid to the appropriate representativeness of the group surveyed.

It also should be noted that this index is not intended as a diagnosis tool of individuals' vulnerability. It is possible for false positives or false negatives, i.e., individuals with index-based vulnerability either side of the threshold who may/may not be considered vulnerable if their situation was considered in isolation. Analogous to BMI (body mass index) as an indicator for obesity, one must remember that the index is only an indicator, and rely on the false positives and false negatives canceling themselves out given a sufficiently large sample size. Similarly, the index is not appropriate for use as in guiding specific actions; the needs and problems of the various aspects making up vulnerability are (likely) too disparate.

5.2. Policy and Planning Implications

The paradigm of automobile-centric urban planning is accompanied by many negative side effects, including air pollution, traffic congestion, deaths and injuries from accidents, the decline of public transport services, environmental degradation, greenhouse gas emissions, susceptibility to oil price fluctuations, visual intrusion, and, especially relevant for this paper, a lack of accessibility for the urban poor [26]. These developments have been particularly marked in developing countries (e.g. Brazil), where large-scale and rapid urbanization pushed authorities and facilities beyond their capacities. New (especially poor) city-dwellers had no choice but to move to the periphery, creating long commutes for jobs, which affected public transport supply and quality. Also, these (unplanned) settlements had/have poor access to urban

services, exacerbating existing problems and the stratification of social groups [27]. Climate change is likely to put further pressure on cities' transport systems, and if not properly managed, the pressure will likely be brought to bear on those transport users whose needs are presently not being adequately met by the systems.

Besides the social benefits of addressing accessibility in transport planning, accessibility is accompanied by co-benefits, with much research showing that well-organized and planned transport systems addressing the accessibility of all users also tend to perform well concerning environmental and economic aspects [28–31]. Accessibility-related vulnerability (and by extension its sustainability) can be addressed via the provision of viable alternatives to personal cars for as many residents as possible. For example, infrastructure and services for active modes (cycling and walking) should be extensive, of high quality, and safe to use. The same applies to public transport services, with the addition of affordability of tickets for lower-income residents, and the physical accessibility of train stations and buses for disabled users or users with children. Finally, attention should be paid to ensuring sufficient services (e.g., jobs, shopping, leisure, and education) in reasonable proximity to (all) residents' place of residence to reduce the need for trips or shorten their length. There is also concurrence between the characteristics that influence accessibility and the resilience of transport systems (shorter distances, modal choices, more cycling and walking), so increasing the accessibility of a city also contributes to its transport system being more resilient [32,33], and thus better able to deal with changes or disturbances, including those brought on by climate change.

However, care must be taken with the approach adopted to examine accessibility, especially using spatial accessibility models such as that used by the United Kingdom (UK) Department for Transport and as outlined in Büttner et al. [34] and Fuglsang et al. [35]. Preston and Raje [36], referring to the UK Department for Transport's accessibility planning approach, said that "although this initiative is not totally without merit, the resulting analysis may be too aggregate, both spatially and socially."

With suitable modifications to the ways in which vulnerability is defined and the responses weighted to reflect local conditions and problems/challenges (e.g., using the methodology provided by Castillo and Pitfield [25]), it is possible to use this vulnerability index to avoid this type of spatial aggregation. By applying it, the approach shifts from aggregating characteristics and deriving vulnerability from them (losing valuable and crucial multi-dimensional aspects in the process), to assessing individuals' vulnerability characteristics and aggregating overall vulnerability. With such an approach, cities, or districts within cities, can be evaluated and compared, and used to identify (at least initially) priority areas where more resources should be allocated, as has been identified as a need in Niehaus et al. [37], especially in Latin America.

By easing and organizing the recognition of vulnerable groups, the index makes keeping track of the transport system's treatment of these groups easier and (more) organized. As such, it can be used to track the progress of the transport system over time. This is particularly relevant in cities wherein the pace of development is great, especially the pace of development regarding congestion reduction, which tends to favor commuter/worker-centric measures, often at the expense of other groups. In the worst case, congestion reduction measures can create vulnerable groups by reducing their accessibility, so the continual monitoring of and attention to vulnerability is vital in order to maintain the equity of the transport system.

5.3. Transferability and Applicability in Other Locations and Projects

The vulnerability index introduced here is fundamentally applicable in other locations and projects. However, the types of vulnerability and the weighting applied would need to be updated to reflect local conditions. Income should be reconsidered especially: in the Netherlands, monthly income below €999 was allocated the maximum five points. Whether a monthly income of €1000 (or equivalent) makes someone vulnerable or wealthy depends entirely on local conditions, particularly the cost of living and cost of transport. Similarly, females, disabled people, or parents (or any other group) may be particularly poorly or well served by their local transport system, so the points allocated

to those responses should be adjusted accordingly. Independent local or national guidelines on poverty thresholds and other forms of vulnerability may be available; these can be used if available. Finally, other vulnerable groups may be present in other locations (e.g., residents of informal settlements); appropriate questions and responses should be provided for them based on existing local knowledge or research.

6. Conclusions

The vulnerability index developed is useful in organizing the responses to a questionnaire completed in Enschede, and from that addressing the EMPOWER project's key performance indicator concerning responses from vulnerable people, based on various individual characteristics in a multi-dimensional manner. The analysis found the response rate of vulnerable people to be 23–36%, depending on the threshold for vulnerability, compared to 1–54% on a question-by-question basis.

With suitably modified indicators and their weighting to reflect local conditions and be more robust, the index could be used in many other locations to organize and aggregate an analysis of users' vulnerability—according to their accessibility—be they questionnaire respondents or inhabitants of a city or districts within a city.

Further work is needed to define aspects to include in a vulnerability index and questions to ask to obtain that information, whether these are either universal or setting-specific. Further, a quantitative and objective method to allocate weightings to the responses would improve the reliability and replicability of the index.

Funding: This work was completed as part of the EMPOWER project, a research project funded by the European Union's Horizon 2020 research and innovation programme (grant agreement no 636249).

Acknowledgments: The author would like to thank the EMPOWER team for their collaboration which contributed to this work, especially Benjamin Groenewolt and Amelia Huang from the Enschede Living Lab for completing the questionnaire, which served as the basis for this article, and sharing the results with me.

Conflicts of Interest: The author declares no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

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