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# Vulnerability Of Charging Infrastructure, A Novel Approach For Improving Charging Station Deployment

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**Abstract**

Since the first uptake of electric vehicles, policy makers are questioning how to rollout public charging infrastructure in an efficient manner, such that user convenience balances with costs of investment. In some metropolitan areas, the first phase of rollout has been passed, meaning an optimized deployment of future charging stations for electric vehicles (EVs) becomes important to improve the charging infrastructure and ensure customer satisfaction and sufficient service provision. Complex system literature shows that network vulnerability is an important metric, yet, charging infrastructure has not yet been a subject of these simulation models so far. This research, based on real-world data, provides a novel approach for improving the roll-out strategy of municipalities, by treating the charge infrastructure as a complex network of charging stations and defining vulnerability in respect to the availability of its surrounding charging stations within relevant walking distance.

*Keywords:* Electric Vehicles; Charging Infrastructure; Cascading Failure; Simulation; Vulnerability Measures; Charging Station Deployment; Complex Network Analysis

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## 1. Introduction

With an awareness of how they can contribute to cleaner air, Electric vehicles (EVs) have captured the attention of relevant stakeholders across the globe. The Netherlands is one of the frontrunners when it comes to electric mobility and advertising its cleaner air quality benefits. By having incentivising policies such as tax reduction and deployment of necessary charge infrastructure, the Netherlands tries to attract more people to make the change from conventional cars to EVs (Ministers van V&W 2011). One of the policies states that each new user of an EV can apply for a new charging station (Ministers van V&W 2011). Thereby, The Netherlands ensures that users have an available charge location in their neighbourhood (Amsterdam Elektrisch, 2016). Furthermore, Amsterdam prioritises EV users by providing free parking in the city centre (Amsterdam Elektrisch, 2016).

Despite these efforts and an increased EV use, potential EV users still experience an insufficiency in EV convenience. This may be explained due to limited driving ranges, high purchase costs, and an underdeveloped charge infrastructure (van den Hoed et al. 2014). This insufficiency is also due to the fact that EV users wish to not only charge their EVs at home but also distant from their place of residence.

In order to overcome this insufficiency, research has taken different angles to improve the infrastructure. This has been initiated by looking at different deployment strategies for charging stations and EV user's charge behaviour. In order to analyse the efforts and efficiency of implementing additional charging stations by the municipality, Spoelstra and Helmus (2015) assessed the different current deployment strategies: demand-driven versus the strategic. Deployment strategies refer to the decision making of where additional charging stations are needed (He et al. 2015). The demand-driven strategy refers to the implementation of charging stations after the request from a new EV user, while strategic deployment refers to the implementation of charging stations at popular public locations. Their findings concluded that both strategies should be used by municipalities (Spoelstra and Helmus 2015). This is because demand-driven deployment provides infrastructure in residential areas, while strategic deployment covers public locations such as shopping centres.
By understanding the charge behaviour of EV users, research has tried to comprehend how municipalities could cater for the needs of EV users (Spoelstra 2014; Franke and Krems 2013). Spoelstra (2014) found that users have a routine charging behaviour. In other words, users charge their EVs not based on battery level but on convenience. Additionally, he found that users usually do not deviate from their customary charging station, which suggests that users are not willing to accept long detours to charge their EVs. In this way, EV users differ from users of conventional cars, who usually find a petrol station once their tank is almost empty.
This leads to the availability problem. In his research, Spoelstra (2014) found that EV users usually charge their vehicles simultaneously at a certain time of the day, which coincides with the common working hours. This may cause an insufficient availability of charging stations at these common times. Spoelstra (2014) concludes in his research that charging station availability is not yet an issue in the Netherlands. However, with an increasing number of EV users, it may soon become a problem. This gives reason to monitor the changing availability of charging stations, in order to prevent issues and dissatisfied EV users.

What has been lacking in EV research is a measure of the effect of charging station failure on other EV users. A failure of a charging station may be seen as a malfunctioning charging station, or another EV user wanting to charge their car at the same place and time. Both cases mean that the user cannot charge their EV at the usual charging station and that an alternative charging stations needs to be found. This may cause inconveniences for the EV user of the alternative charging station, who now may also need to find an alternative. This effect is referred to as cascading failure. The effect of cascading failure on the charging infrastructure can be measured by treating the charging infrastructure as a complex network.

### *1.1. State of literature*

A considerable amount of research has been conducted on simulating cascading failures of complex networks (Koc et al. 2013; Zeng and Xiao 2014; Zheng et al. 2007). A complex network, is a network with non-trivial topological features, and is usually used as a representation of a real-world system. Several studies on that topic have been conducted with a focus on electric distribution networks such as power grids, in which a failure may occur due to extreme weather conditions or human errors (Zhang et al. 2011; Dobson et al. 2007; Bao et al. 2009). By simulating the failure of a charging station it is checked where the load of the failed charging station is redistributed to, and whether this leads to a failure (due to overload) at the alternative.

A lot of analogies can be seen between an electric distribution network and the charge infrastructure. The nodes in the charge infrastructure network refer to charging stations, edges refer to the connections between alternative charging stations, and its capacity refers to the number of sockets. The load can then be seen as the current amount of EVs charging at the station. A network allows for simulations of charging station failure in order to measure how cascading failure affects other EV users of the alternative stations. If a station fails, the load (the charge transaction on that charging station) needs to be redistributed to an alternative charging station. The failure may lead to an overload in other parts of the network.

Li et al. (2013) defines a vulnerable network as a network that cannot redistribute the load to other nodes. In general, node vulnerability refers to its susceptibility to a disruptive event. In order to identify the most critical (most vulnerable) charging stations, centrality measures such as degree, betweenness, closeness and eigenvector centralities are commonly used (Albert et al. 2004; Albert et al. 2000). These centrality measures do not account for the effect on other charging stations. Therefore, this paper defines two new vulnerability measures to account for this effect. The first measure - *Service Failure Vulnerability* - determines the fraction of charge transactions that cannot be accommodated by the network. The second measure - *Inconvenience Vulnerability* - counts the number of failed charging stations as a result of a single initial charging station failure. The higher the vulnerability measure, the more vulnerable the charging station. By simulating cascading failure and measuring its effect on EV users, a vulnerability score for both measures can be calculated. For this purpose, the municipalities of Amsterdam, Rotterdam and Utrecht made available a database of charging transactions, which allows the retrospective simulation of the effect of cascading failure on EV users.

Using these measures, this paper introduces a novel approach that aims to improve future deployment of charging stations within the charging infrastructure. By determining the most vulnerable charging stations within the infrastructure network, this paper provides valuable information for municipalities and policy makers to make considered decisions about future charging station deployment and maintenance. The new vulnerability measures can give an indication of the need for additional charging stations, at residential as well as public places. By deploying additional charging stations, municipalities may be able to reduce the vulnerability of charging stations and provide a sufficient charging infrastructure. This may attract new EV users.

## 2. Methodology

In this paper, cascading failure refers to the effect of the failure of a charging station on other EV users. This will be modelled by retrospectively simulating the failure of a particular charging stations for a certain month. For the purpose of simulating failing charging stations a unique database is used, containing the information of approximately 5,000 public charging stations, with more than 2 Million observations of charge sessions of approximately 40,000 users. This database was made available by the municipalities of Amsterdam, Rotterdam and Utrecht. It contains data from 1st of January 2014 and new data is added each month. A detailed description of the data can be found in (van den Hoed et al. 2014). The model that simulates the cascading failure of the charge infrastructure network consists of three parts: network model, reaction to failure, and relevant measures.

### *2.1. Network model*

In order to simulate cascading failure in the charging infrastructure of EVs, a network model is needed that connects relevant charging stations. A relevant charging station is a charging station that EV users would consider in case of failure of their usual charging station. The nodes of the network represent all the charging station locations within the city, and the edges of the network are undirected connections between relevant alternative charging stations. Since there is not a predefined distance an EV user would consider, it may be derived that users would only consider close-by charging stations as alternatives (Spoelstra and Helmus 2015; Spoelstra 2014; Azadfar et al. 2015). Therefore, this paper will compare radiuses of 400m to 600m in order to make a sensitivity analysis. These radiuses will be referred to as relevance radiuses. Figure 1 shows the infrastructure network of Amsterdam, when considering a relevance radius of 500m.

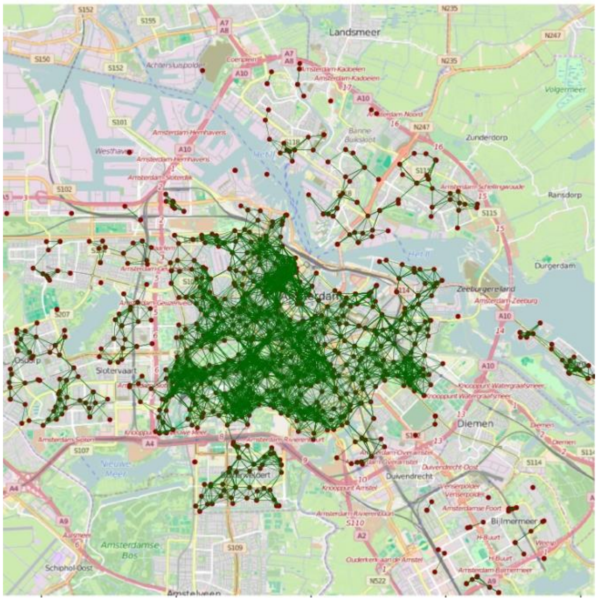

Fig. 1 Infrastructure network of Amsterdam (relevance radius 500m). Each node represents one of 764 charging locations, each edge represents a connection to a relevant alternative.

### *2.2. Cascading failure model*

The cascading failure model simulates the failure of a charging station and its effect on other EV users by removing a station from the system and then for each charging session at this removed station it checks how the system (its users) accommodate to this situation. In order to simulate cascading failure, the reaction of EV users to failing stations needs to be considered. Once a charging station fails (a node is removed), the user needs to find an alternative charging station, where the charge transaction can be redistributed to. In order to check whether the charge session can be redistributed, it needs to be seen whether the failed station has any relevant alternatives (see section of network model). If not, all the charge transactions of the failed charging station fail to be redistributed, and cannot be accommodated by the network. However, if the charging station has relevant alternatives, for each charge transaction it will be checked whether the whole transaction can be accommodated by one of the alternative charging stations.

Each charging station has a maximum capacity of EVs it can charge at the same time. This amount is 2 for most of the charging stations. If at least one of the alternatives has 1 free charge socket, there is no cascading failure within the network, since the EV user can charge their EV at one of the relevant alternatives. In the case of more alternatives being present, it is assumed that the EV user chooses the closest available alternative.

If the whole charge transaction does not fit into the alternative, it is checked whether an alternative is available for the start time of the charge transaction. If so, the charge transaction that competes for the rest of the time (that is known, since the whole charge transaction could not be accommodated) needs to now find an alternative. The EV user of the competing charge transaction now goes through the same procedure. Therefore, cascading failure occurs. However, if no alternative is available at the start time of the charge transaction a complete failure occurs. This failure is because the charge transaction cannot be accommodated by the infrastructure network. The EV user has no relevant alternative available to charge their EV. For a visualisation of the steps taken for simulating the reaction of EV users in case of failure, see decision tree in Figure 2.

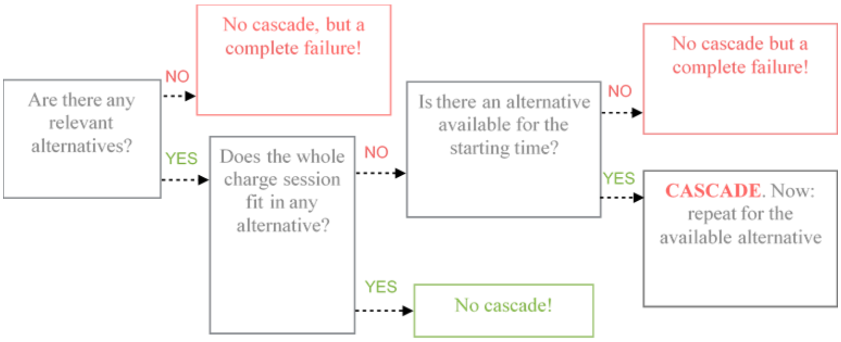


Fig. 2 Decision tree for simulating EV-users reactions to failure

### *2.3. Relevant measures*

In order to give measures for the effect of the cascading failure on EV users, this paper defines two different vulnerabilities: Service Failure Vulnerability and Inconvenience Vulnerability. *Service failure* vulnerability is defined as the fraction of charging transactions that fails to be redistributed to a relevant alternative charging station. It is measured per charging station by dividing the number of sessions that failed to be redistributed over the total number of sessions at that station in a specific month. It refers to the inability of the network to accommodate charge transactions within the network in case of failure.

In the above section on EV users' reaction to a failure, it is assumed that a complete failure occurs if an EV user must traverse more than the distance of the relevance radius in order to find an available charging station for this particular charge transaction. For every charge transaction of the month, it is checked whether a complete failure occurs. The amount of complete failures that occurs during that month on the particular charging station will then be divided by the overall amount of charge transactions of that station, in order to normalise the result. The normalised value is then its service failure vulnerability score. If a charging station has a service failure vulnerability score of 0, it means that all charge transaction could be redistributed over the network, even though it may have had to travel through the network. However, if every charge transaction fails to find an alternative, or the redistribution causes a failure of another EV user's charge transaction, the vulnerability score is 1. To summarise, the service failure vulnerability score only measures whether the network can redistribute the failure of a charging station somewhere in the network, even though it may cause inconveniences for other EV users.

*Inconvenience vulnerability* is defined as the number of EV users a failure of a specific charging station may affect. In other words, the inconvenience vulnerability score is the maximum number of cascades, the length of the chain of charging stations, that the failure of the specific charging station may cause. The minimum length is one and the maximum length that a cascade could travers is the diameter of the component of the geodesic network where the cascade occurs, see Fig 1. As explained in the section on EV users' reactions to a failing charging station, it was seen that if cascading failure occurs it causes inconveniences for other users. Even though this measure does not indicate whether the network is able to accommodate the failed charge transaction, it demonstrates how many users have the inconvenience of deviating from their usual charge station.

To summarise, the inconvenience vulnerability score measures the maximum amount of EV users a failure may impact, without taking into account whether or not the charge transaction can be accommodated by the network.

In order to determine whether these two new vulnerability measures are related to other network vulnerability measures, they were compared to the commonly used centrality measures (Albert et al. 2004; Albert et al. 2000). These centrality measures are node degree centrality, betweenness centrality, closeness centrality and eigenvector centrality.

The node degree centrality measure gives an indication of whether the vulnerability measure is related to the number of alternatives a charging station is connected to, while the betweenness centrality refers to the number of shortest paths from all charging stations to all others that paths through that node. The closeness centrality measure of a node refers to the sum of distances to all other nodes. In other words, it gives a measure of how close the node is located to all other nodes. Lastly, the node with the lowest closeness centrality measure is located most central and has the shortest path to any other node. The eigenvalue centrality considers a charging station vulnerable if many other vulnerable charging stations are connected with it. Thereby, it gives a vulnerability measure in respect to the connectedness of the neighbours.

## 3. Simulation results

In this section, the findings for the city of Amsterdam will be discussed in detail. Amsterdam is chosen as the case study, since it has the most developed charge infrastructure with the most charging stations. Charging stations with its corresponding vulnerability scores for both vulnerability measures were plotted (Figure 4a and 4b). This is done to get an initial understanding of where the most vulnerable charging stations are located in regard to service failure vulnerability and inconvenience vulnerability.

The distribution of charging stations with high vulnerability scores in terms of service failure vulnerability shows that these charging stations are located in the outskirts of the city (Fig. 4a), while charging stations with a high inconvenience vulnerability score are located in the city centre (Fig. 4b). Furthermore, it can be seen that for the service failure vulnerability measure there is hardly any variation in vulnerability scores. Most charging stations have a vulnerability score of 0, while 16 stations have a score of 11 (Fig. 4a). Hardly any other values are found in between. In contrast, the inconvenience vulnerability measure has a variety of vulnerability scores (Fig. 4b). In appendix A the distributions of both vulnerability scores can be found in Fig 5. and Fig. 6.

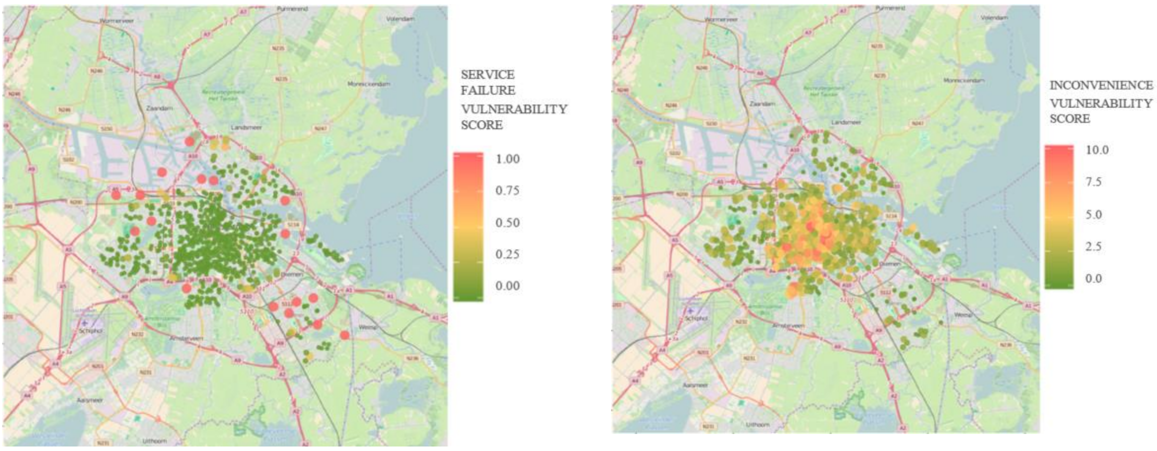


Fig. 4 (a) Service failure vulnerability scores (b) inconvenience vulnerability in Amsterdam, December 2015 (relevance radius 500m).

So far, findings have only been discussed for a relevance radius of 500m. The question occurs whether this distance is indeed a good representation of the behaviour of the network. A sensitivity analysis on the histograms of vulnerability scores only appeared to have minor changes, suggesting that the charging infrastructure is insensible to changes of the relevant radius. Therefore, 500m is a reasonable choice, and its findings represent the behaviour of the network with only minor deviations.

The differences in spatial distribution of the two vulnerability measures suggest that the two vulnerability measures are not related (Fig. 4a and 4b). Vulnerable charging stations in terms of service failure are located mostly on the outskirts of the city, while vulnerable charging stations in terms of inconvenience vulnerability are mostly located in the city centre.

Indeed, when calculating Pearson product moment correlation coefficient to determine the relationship between service failure vulnerability and inconvenience vulnerability, only a weak negative correlation of -0.19 was found (Fig. 5). This result is significant at the $p = 0.05$ level; however, it explains very little variance of the relation between these two values. In an effort to understand the difference of their spatial distribution, the two vulnerability measures were compared to the four commonly used centrality measures in network analysis, namely node degree, betweenness, closeness, and eigenvector centrality. The correlation matrix is visualised in Fig. 5.

By looking at the maps (Fig. 4a and 4b) it may be expected that the two vulnerability measures are related to node degree, since it seems like charging stations on the outskirts of the city have fewer alternatives than charging stations in the city centre. Surprisingly, only a weak negative correlation (-0.31) between service failure vulnerability and node degree centrality was found, while a moderate correlation (0.48) was found between inconvenience vulnerability and node degree, which explains almost 25% of the variance (Fig. 5).

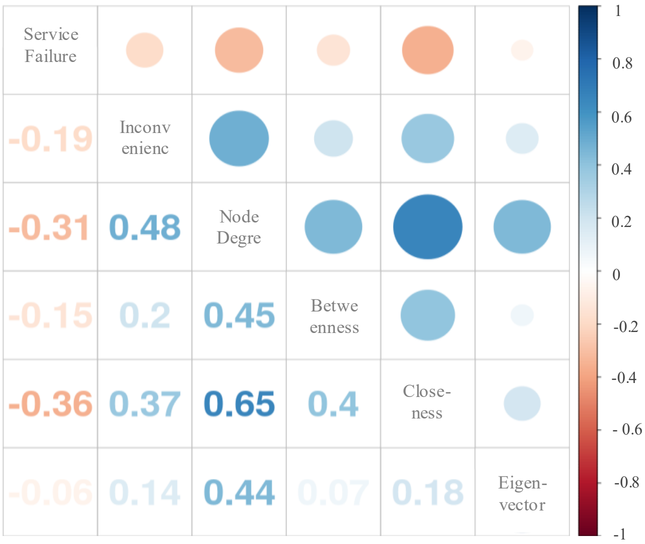


Fig. 5 Correlation Plot Between Centrality Measures and Vulnerability Measures in Amsterdam, December 2015 (Relevance Radius 500m).

Since node degree and closeness degree were found to have a strong correlation (0.65) it is not surprising that the closeness centrality measure also has a moderate correlation with service failure vulnerability and inconvenience vulnerability (-0.36 and 0.37 respectively). Furthermore, a weak (negative weak) correlation between the betweenness centrality measure and the inconvenience measure (service failure measure) was found (Fig. 5). An even weaker correlation was found between eigenvalue centrality and the two vulnerability measures. A correlation score of -0.06 was found between eigenvector centrality and service failure vulnerability, and a score of 0.14 between eigenvector centrality and inconvenience vulnerability (Fig. 5).

## 4. Discussion

The findings suggest that the two vulnerability measures - service failure vulnerability and inconvenience vulnerability - are orthogonal to each other, which means they are statistically independent. Even though a weak negative correlation was found, this does not suffice to explain the variance of the occurrence.
Further, by seeing the city map with their charging stations plotted by vulnerability score, it became apparent that the spatial distribution of the two vulnerability measures are unrelated to each other. High vulnerability scores in terms of service failure vulnerability were only found on the outskirts of the cities, while high vulnerability measures in terms of inconvenience vulnerability were found in the city centre and appear to be related to network density.
In order to determine whether the differences of spatial distribution of the two measures could be explained by other measures commonly used in complex network analysis, the two vulnerability measures were compared to node degree centrality, betweenness centrality, closeness centrality and eigenvector centrality. The results show that a weak to moderate correlation was found between the two vulnerability measures and node degree, as well as closeness centrality and vulnerability measures. Indeed, this gives an indication that charging stations with a high service failure vulnerability are located in less dense areas, while charging stations with a high inconvenience vulnerability are located in dense areas such as the city centre. However, only little variance is explained by these findings, which suggests that it is does not suffice to check for network density in order to identify charging stations with high vulnerability scores for either of the new vulnerability measures.
For the correlation betweenness centrality and the two vulnerability measures only a weak correlation was found. That finding is not surprising, since the cascading failure simulation does not give a measure to charging stations that are effected by another charging station. The model only gives a score to the (hypothetically) failed charging station. If this model of the cascading failure simulation would have measured the likelihood of a charging station being affected by another charging stations' failure, the betweenness centrality measure would potentially have a

higher correlation. The very weak correlation scores between either of the two vulnerability measures and the eigenvector centrality measure suggests that almost no relation can be seen between the vulnerability score of a charging station in relation to the vulnerability scores of the neighbouring stations. Overall, the comparison to the centrality measures shows that if checking for the most vulnerable charging stations in regard to failure, it does not suffice to check for commonly used centrality measures.

These findings suggest that due to the orthogonality of the two new vulnerability measures and the dissimilarity to other network centrality measures, it is now possible to answer the first question; should municipalities consider both new vulnerability measures before deploying further charging stations? Since no other measure gives an indication for the weaknesses of the infrastructure network in terms of failing charging stations, the answer is yes. It is highly recommended to consider the findings of both vulnerability measures before making decisions about future charging station deployment.

This suggestion also leads to the second question: in which regions should municipalities consider deploying additional charging stations? The two new vulnerability measures, give insight into very different effects of failure on EV users. The service failure vulnerability measure is a way of measuring whether the charge transactions of the failed charging station can be redistributed to alternatives. The results of the service failure vulnerability indicate which charging stations do not have alternative charging stations in case of failure to accommodate the charge transactions. On the other hand, the inconvenience vulnerability measure gives an indication about how many EVs may be affected, by determining how many EV users would need to deviate from their usual charging station. In order to make a considered decision it is recommended to monitor the changes of vulnerability scores over a period of time, in order to be able to determine the most vulnerable parts of the charging infrastructure.

The spatial distribution of the vulnerability measures gave clear indications into which areas are most affected by different effects of charging station failure on EV users. Only on the outskirts of the city centre, charging stations had high service failure vulnerability scores. In contrast to that, the most vulnerable charging stations in terms of inconvenience vulnerability were found in the city centre. The city maps in the results section, give a visual overview about the corresponding vulnerability score of charging stations. However, the question about need of additional charging stations is not answered yet.

The findings of this paper may help to point out the weaknesses of the charging infrastructure. On the one hand, municipalities need to make sure that EV users are provided with a sufficient amount of charging stations, in order to allow them to charge their EVs, whenever they need to. On the other hand, it is important to keep EV users satisfied, in order to attract more new EV users. Therefore, it is suggested that municipalities implement additional charging stations in the areas where charging stations are vulnerable in terms of either one of the two vulnerability measures. Since the two measures appear to be orthogonal, both measures should be taken into account before deploying additional charging stations.

Although the study has successfully demonstrated the effect of cascading failure on EV users, it has a number of important limitations that need to be considered. Firstly, even though suggestions about future charging station deployment could be made, it is important to state that municipalities also need to consider other factors than just the effect of charging station failure on EV users before deploying additional charging stations. It would not be economic for municipalities to deploy an additional charging station in an area where this additional station would only be used in case of the failure of the other station, or in areas where the other stations are already hardly used. The two different measures should be seen as a tool for municipalities to make considered decisions about further deployment of charging stations, in order to improve future charging station deployment.

Secondly, in this simulation the user of a failing charge station is assumed to have total knowledge about the availability of the surrounding charging stations. In the simulation, the user knows which station is available and then chooses the closest available station. Obviously, this is not the case in real life. The EV user would not know which stations is available within his/her relevant radius and may try to charge at several other charging stations before finding an available station. Alternatively, the user may decide not to charge at all, and wait until the next day. The simulation does not accommodate those specifications.

Thirdly, actual statistics of how often a charging station failure occurs is not taken into account. By considering the number of new EV users, and the frequency of charging station malfunctioning, it may be possible to better predict the occurrence of charging station failure.

A natural progression from this work is to implement different reactions of EV users to failure and compare those results to the findings of this paper. Currently, the simulation assumes that an EV user chooses the closest alternatives within a predefined radius. In order to get a better idea which alternative the user would choose, it may be important to take the walking distance and time as a measure of the best alternative. Alternately, it could be assumed that the user of the failed charging station chooses an alternative, based on the charging station they have used before. These different strategies may give a better prediction.

Furthermore, a tool for EV users with which the user could see which alternative charging station is available at the time he/she wants to charge the EV. This may be in the form of a software application (app) or implemented in the charging stations itself, suggesting to which alternative the user should go. That may reduce the inconvenience vulnerability score of charging stations and improve user satisfaction.

## 5. Conclusion

This paper aimed to design vulnerability measures to compute the effect of charging station failure on EVs users, in order to make suggestions about future charging station deployment. Returning to the questions posed at the beginning of this study, it is now possible to state that the two newly defined vulnerability measures give insight into the weaknesses of the charging infrastructure for EVs.

This paper extends the present knowledge of the charging infrastructure network of EV's due to its insights in the effect of charging stations failure. It makes several noteworthy contributions to the improvement of the charging infrastructure.

Firstly, it introduces a novel approach of simulating cascading failure in the charging infrastructure and measuring the effects on EV users. Two different vulnerability measures - service failure vulnerability and inconvenience vulnerability - have been computed using the simulation model of this paper. The service failure vulnerability indicates which charging stations fail to accommodate their charge transaction in case of failure. Inconvenience vulnerability measure gives an indication about how many EV may be effected, by determining how many EV users would need to deviate from their usual charging station. The newly introduced vulnerability measure was found to be unrelated to commonly used network centrality measures, which suggests that the new measures should be considered by municipalities.

Secondly, suggestions for future charging station deployment can be made based on the spatial distribution of charging stations with high vulnerability scores. It is recommended to implement additional charging stations on the outskirts of the city, in order to reduce service failure, and in the city centre in order to reduce inconveniences for EV users in case of charging station failure. However, these measures should be seen a tool to determine the weaknesses of the charging infrastructure network, rather than the only measure that needs to be considered for decision making. By monitoring the vulnerability measures over time, it may allow to monitor changes of the network and predict future weaknesses. This prevents EV user dissatisfaction and may attract new EV users.

The key strengths of this study is its real-world data. All findings are based on simulations with real-world data by retrospectively looking back at it. That allows to draw conclusions over the past and give precise suggestions where improvement is needed. While in this paper only considers conclusions for the city of Amsterdam, the results from other cities showed similar patterns. Future research may therefore extend to cities.

An third improvement of the current work would be to combine the vulnerability simulations with predicted local user adoption and behaviour. Simulation of future adoption may be distilled from extrapolation of historical adoption and charging behaviour can be achieved by an Agent Based simulation Model (ABM) based on the historical charging data. Added users may be given charging behaviour similar to their local peers (Helmus and van den Hoed, 2015). The predicted charging sessions resulted from the agent based model may then be used in the vulnerability simulation in order to check the effect of new users on the charging infrastructure. This would enable policy makers not only to manage charging infrastructure vulnerability based on historical sessions but also on future scenarios. To the best of the researchers knowledge the combination of both simulation models has not been presented in literature yet. Future research may therefore focus on development of an ABM based on the charging data and then combining both models.

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## Appendix A – distribution of vulnerability scores in Amsterdam

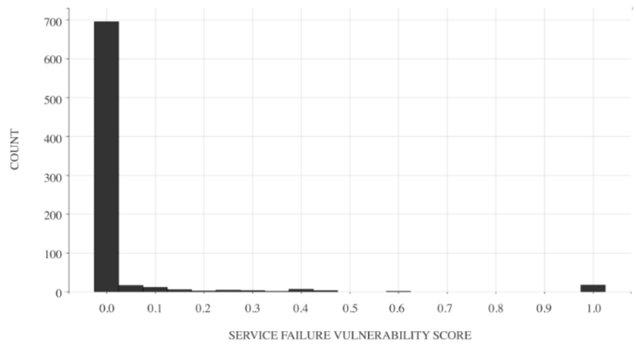


Fig. 6 Histogram of service vulnerability scores in Amsterdam, December 2015 (relevance radius 500m).

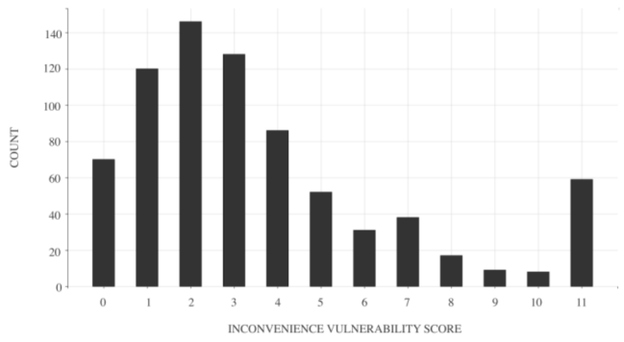


Fig. 7 Histogram of inconvenience vulnerability scores in Amsterdam, December 2015 (relevance radius 500m)