Vulnerability and risk analysis of the road infrastructure in Reykjavík

Áhættu- og áfallaþolsgreining vegakerfsins í Reykjavík

31. March 2008

Línuhönnun
verkfræðistofa

Information

Prepared by: Jens Bengtsson, Böðvar Tómasson		**Client:** Vegagerðin
Date: 2008-03-31	**Report number:** Ra01	**Status:** Preliminary report
Project Manager: Böðvar Tómasson		**Controlled by:** Böðvar Tómasson
Type of report: Risk Analysis		
Report name: Vulnerability and risk analysis of the road infrastructure in Reykjavik		
Summary: A methodology has been presented for risk and vulnerability analysis of a road network. A simplified screening approach can also be applied where the most vulnerable links are identified and such an analysis carried out for the road network of Reykjavik.		
Key words: Risk analysis, vulnerability, infrastructure, road network, hazards, Reykjavík,		
Saved on: M:\Vegagerðin\Áhættugreining Rvk\		
Project number: VR7RA		**Number of pages:** 41

Distribution:

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History

Nr.	**Prepared by** (name/date)		**Checked by** (name/date)		**Approved** (name/date)	
1	**JEB/BT**	**2008-03-31**				
	Preliminary report					
2						
3						

Contents

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2. Summary

In this project, a methodology has been presented for risk and vulnerability analysis of a road network. This methodology takes into account the hazards associated, their probabilities and their consequences with a road network and how to calculate the overall risk and vulnerability in the network. Risk is usually defined as the probability of an event multiplied with the consequence of the event. Vulnerability has in this report been defined as a measure based on the accessibility between different nodes in the network. A link is considered to be critical in the case that the closure of the link results in large increases in travel times or that there is a large of trips that cannot be performed because of the failure of the link.

The identification of vulnerable links is vital since it is practically impossible to make an in-depth risk analysis of every single link and thus it is of great importance to identify the links that is most vulnerable and perform a more detailed risk analysis of these links. The most comprehensive method of doing this is to remove each link one by one to look at the number of uncompleted trips and the overall increase in travel time for each such link and using this a measurement of the vulnerability. A simplified screening approach can also be applied where the most vulnerable links are identified by ocular analysis where the links are evaluated based on the traffic load, the redundancy and the physical properties of the links. The advantage with this simplified method is that the analysis is less time consuming and at an initial state it will be able to identify the most vulnerable links. The disadvantage is that the risk and vulnerability is not quantifiable with this approach and is only qualitatively analyzed.

The next step in the methodology is to identify and analyze the existing hazards at the vulnerable links. In this report the most common hazards that the Icelandic road network is subject to have been identified and analyzed based on their properties. The hazards have been categorized in the 5 categories: accidents, natural disaster, weather, hazards in the infrastructure itself and deliberate acts, to get a transparent approach to the risk analysis at different parts of the road network. By applying this hazard identification to potentially vulnerable links the risks at each location can be identified and to some extent also quantified.

Using this method, Vegagerðin will be able to choose the alternative that will lower the overall risk to the society the most and thus is the most efficient choice in that respect. The method might also be used for the planning of future roads for an increasing transportation demand e.g. in the Reykjavik capital area. It will therefore be a practical method when comparing alternatives of the general road network and choosing between different alternatives since it will be able to show how the network will be able to perform under different constraints and how much the a new link will reduce the vulnerability of the network. It will also be possible to take the cost of the investment and compare this cost to the reduced risk cost in the network and thereby get a measurement of the effectiveness of the investment. Correctly used it will also create the possibility to pinpoint resources to those projects that will lower the overall vulnerability and increase the reliability of the Reykjavik road infrastructure the most.

The simplified vulnerability methodology presented above was applied to the road network of Reykjavik, where the hazards that the network is subject to have been identified and analyzed and to some extent also quantified. Three links in the network were identified to be among the most vulnerable and were therefore analyzed from a vulnerability perspective. The three identified links had several properties in common, they were all heavily trafficked multiple lane roads with a low redundancy. Further all the links had at least one bridge or aqueduct along the studied part making them subject to potentially large consequences. However, considering the difference in the design and redundancy there were still some differences between the three links.

The analysis can at a later stage be extended further to include computer simulations of the road network. The vulnerability of the system as a whole would then be simulated with stochastic accidents and other possible events to simulate the full effects of the closure of certain links. This approach will also make it possible to reduce the capacity of the links simulating the effect of only partial closures and thereby see how different events will affect the performance of the network.

3. Introduction

3.1 Purpose and goal of project

The objective of this study is to outline a method for vulnerability and risk analysis of the road infrastructure in Reykjavik. This kind of studies have received more and more attention lately and it is especially import to conduct such a study in Reykjavík since roads are the only way of transportation by land in Reykjavík and thus they are crucial for the society to work properly. The road network is not just important as a mean of transportation but also in assisting, maintaining and repairing other infrastructure and for evacuation in case of disasters. This fact as well as the fact that more and more industries turn to just-in-time solutions to increase their productivity makes it crucial for Reykjavík to have a resilient infrastructure to continue to be an attractive place to live and invest in.

The goal of the project is therefore to set up a model that is able to identify the most vulnerable parts of the Reykjavik road infrastructure. This will be done by combining the probabilities and consequences of disturbances in the road network to get an overall measure of risk. By doing this we will also create a method that can be used when choosing between different options of improvements of the Reykjavik road infrastructure today.

3.2 Background

In the society of today the road network is of great importance. As cities grows so does the needs of transportation and this puts an increased pressure on the infrastructure. Thus it is of great importance to have a reliable and redundant infrastructure for the traffic, to make sure that it works even during bad conditions. There are several different hazards which may have an impact on the road infrastructure such as for example natural catastrophes, accidents or failure of parts of the road network. Since the different infrastructure systems get more and intertwined in the society of today and the society becomes more vulnerable for catastrophes, these hazards might have effects on other infrastructure systems as well. Thus more and more researchers start to look at the risk of possible cascaded consequences in interconnected networks. This study will however mainly focus on the road infrastructure.

The interest in road network vulnerability and reliability studies has existed for at least a decade. Events like the earthquake in Kobe in Japan in 1995 and the terrorist attacks have drawn increased attention to these questions [4]. Thus there have already been some works done in this field throughout the world but never in Iceland and no studies that have combined the probabilities and consequences of disturbances in the road network to get an overall measure of risk. However, similar network studies have already been made in Stockholm [1] where 5 bridges where identified as the most vulnerable links in the transportation network and them malfunctioning summed up to several millions SEK a day. The cost was calculated as the increase total travel time multiplied with the Swedish official travel time value (35 SEK/hr). In this study it was assumed that everyone had perfect information regarding the state of the road network and it was just a question of private trips which means that the actual cost is a lot higher. There have also been studies conducted in New Zealand [2] where the researchers focused on state highway system and the hazards present to this system. A study in Australia [3], the researchers focused on the accessibility from the rural parts and the overall vulnerability of the road network.

The use of road network vulnerability and reliability will in a longer perspective be a helpful tool in several different fields. In for example incident and contingency planning, and the planning of road works awareness about the impacts of reduced capacity on links could significantly reduce the disturbances of the traffic. Increased efforts in maintenance and surveillance should also be put on links or parts of roads that are critical to the system. To make such a distinction there is a need to find general measures of the criticality of links in the network and the vulnerability of sites, municipalities etc. need to be developed and tested. [4] This is the point where the most of the research is focused today and as will be shown later in this study, there are several different methods of setting up such a model.

3.3 Scope

This project has focused on creating a tool for risk and vulnerability analysis of the Reykjavík capital road network. Since the Reykjavík area is a relatively large area a macroscopic travel, instead of microscopic, model are preferred to simulate the effects of different events. Considering the size of the network the risk analysis will be limited since it is practically to account for all possible risks at every single road. We have, however, at the most vulnerable roads made a more in-depth risk analysis to try to quantify the risks at these roads.

4. Reliability models for networks

The conception of reliability has a widely accepted definition “Reliability is the probability of a device performing its purpose adequately for the period of time intended under the operating conditions encountered.” [18] However, when it comes to the conception of road network reliability there have been large number of different definitions throughout the years and in table 1 a few of these reliability measures are presented.

Table 1. Differentt measures of reliability for road networks. Based on table in [6]

Reliability	**Performance indicator**	**Uncertainty**	**Constraints**	**Probability Definition**
Connectivity [7]	Connect or disconnect	Disruptions of road links	Not included	Connected and disconnected network
Travel Time (I) [8]	Specified travel time (T)	Fluctuations of daily traffic flow	Constant demand and no link capacity	Travel time less than T
Travel Time (II) [9]	Specified network service level (L)	Degradable link capacity	Constant or elastic demand function and link capacity constraint	Service level less than L
System and OD sub-system [10]	Intolerable decrement of OD flow (E)	Degradable link capacity	Elastic demand function link capacity constraint	Decrement rate less than E
Capacity [11,12]	Required demand level (Q)	Degradable link capacity	Proportional OD trip table and link capacity constraint	Network reserve capacity greater than Q
Travel time budget [13,14]	Travel time budget for punctual arrival	Degradable link capacity	Constant total demand	Within budget time reliability
Travel demand	Specified travel demand	Travel demand and degradable	Elastic demand function	Travel demand satisfaction ratio

satisfaction [15]	satisfaction ratio	link capacity		less than S
Road vulnerability [1]	Travel time and serviceability	Demand fluctuations and incidents	Consequence of incidents	Probability for an incident to occur

As earlier mentioned, it was not until during the beginning of the 1990s as network reliability really received attention as a research topic. Especially the Kobe earthquake in 1995 and its aftermath stimulated an interest in so-called *connectivity reliability*. Connectivity reliability focuses on the probability that a pair of nodes in a network remains connected to each other – which means that there is a connected path between them – even though one or more links in the network have been cut. Figure 1 shows an example of infrastructural network with high connectivity reliability since there are alternative routes between all zones. The subsequent research following the connectivity reliability was focusing on degraded networks, usually urban road networks subject to traffic congestion. In these studies the networks remained physically intact but the performance of one or more links could be so severely affected by for example congestion that their use by traffic is curtailed. This led to the definition of two additional forms of reliability: travel time reliability and capacity reliability, as described below. [5]

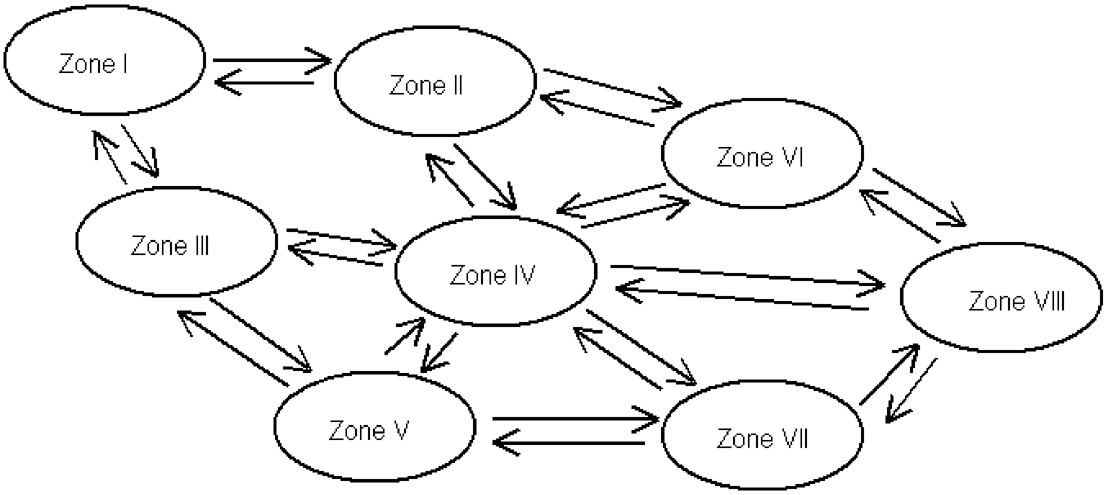

Figure 1. An example of an infrastructural network.

The term *travel time reliability* considers the probability that a trip between from one point to another can be completed successfully within a certain time. The travel time reliability might be affected by differences in link flows and the fact that the driver not has perfect information available. Another term worth mentioning in this context is the *link travel time variability* which is the variation for the distribution of individual travel times. Measures of travel time variability are useful in assessing network performance in terms of service quality provided to travellers on a day-to-day basis. [5] However, since link travel time variability mostly considers the natural variation in the travel time from one point to another it is not useful when looking at the vulnerability of the road network.

Another way of looking at the network performance in congested networks is to look at it from the supply-side performance which has been called *capacity reliability*. Capacity reliability has been defined as the probability that a network is able to support a given level of demand. In this case the network may be in its normal state or in a degraded stated (for example because of incidents or road works). Using capacity reliability together with travel time reliability could provide a valuable transport network design tool since it would take into account both the demand and supply side of the network. There have also been studies which have demonstrated [16, 17] how the concepts of travel time reliability and capacity reliability could be used in planning and evaluating traffic management schemes in an urban area.[5]

5. Vulnerability models

In recent years, the issue of road transport vulnerability has received increasing attention. While no firm definition exists yet, many authors agree that vulnerability is closely related to the more established concept of reliability which was discussed in the previous chapter.

The conception of reliability has a widely accepted definition “Reliability is the probability of a device performing its purpose adequately for the period of time intended under the operating conditions encountered.” This definition leads to that reliability studies generally concerns probabilities only, which in fact often is the case. [18] However, reliability arguments based on probabilities and absolute connectivity may obscure potential network problems, especially in large-scale, sparse regional or national networks. In these networks the consequences of a disruption or degradation of the network become important. For example, D’Este and Taylor [19] used the example of the Australian highway network to illustrate the potential consequences of the severance of certain transport connections. In this example the system reliability was considered, in terms of a cut to the Eyre Highway and transcontinental rail line between Perth and Adelaide, for instance by flood. The overall network remains connected and the probability that the route in question is cut by flood or other natural cause is extremely small so the travel time and capacity reliabilities are high. Therefore the established measures of network reliability would not indicate any major problem with the network. However the consequences of network failure are substantial – in this case the next best feasible path through the network involves a detour of some 5000 km. This example illustrates the concept of network vulnerability and the difference between network reliability and vulnerability. It is also easy to draw parallels to Iceland where a cut of Road 1 would create similar consequences. The concept of vulnerability is more strongly related to the consequences of link failure, irrespective of the probability of failure. In some cases, link failure may be statistically unlikely but the resulting adverse social and economic impacts on the community may be sufficiently large to indicate a major problem warranting remedial action – akin to taking out an insurance policy for an extremely unlikely yet potentially catastrophic event. For example, the impact on a rural community of loss of access to markets for its produce and to vital human services (such as a hospital) would be catastrophic. Low probability of occurrence and network performance elsewhere does not offset the consequences of a network failure. Thus network reliability and vulnerability are related concepts but while reliability focuses on connectivity and probability, vulnerability is more closely aligned with network weakness and consequences of failure. [5]

Berdica [1], proposed that vulnerability analysis of transport networks should be regarded as an overall framework through which different transport studies could be conducted to determine how well a transport system would perform when exposed to different kinds and intensities of disturbances. From her study of the road network in central Stockholm she suggested three main questions that might be posed in these studies:

1. How do interruptions of different critical links affect system performance, and to what extent?
2. How is network performance affected by general capacity reductions and possible changes to traffic management and road space allocation in a sub-region of the network?
3. How is the system affected by variations in travel demand?

These questions provide a starting point for the development of a methodology for study of vulnerability in transport networks and infrastructure. They highlight the key issue of the identification of critical components of the networks. Vulnerability analysis is intended to address these questions and the perhaps more important questions that flow from them – when we know where the vulnerable elements (the 'weakest links') of a transport network are, what is the best response, what can we do about it?" [5]

The study of vulnerability extends this risk assessment framework in several important ways. Firstly it extends the region of interest to areas of high consequences and low or unquantifiable (but non-zero) probability of occurrence – on the basis that measurement of occurrence probability and consequences (human and economic) is imprecise for many types of incidents, and society may well consider some consequences to be unacceptable and worthy of safeguarding against, despite uncertainty about their probability of occurrence. Secondly, vulnerability analysis provides a framework for targeting risk assessment. One of the key conclusions of risk assessment of the New Zealand highway network [20] was that it is impractical and financially infeasible to conduct detailed geophysical and other risk assessment across an entire transport network. The costs of deriving accurate location-specific risk probabilities across a range of risk factors are too high to make it viable – what is needed is a way of targeting risk assessment resources to get best value from them. Vulnerability analysis provides another way of approaching this problem. It can be used to find structural weaknesses in the network topology that render the network vulnerable to consequences of failure or degradation. Resources can then be targeted at assessing these 'weak links'. Thirdly, vulnerability auditing admits a more proactive and targeted approach to the issue of transport network risk assessment and mitigation." [5]

To evaluate the vulnerability in the Reykjavik road network an approach that considers an uncapacitated network for which there is a distance (or travel time) and a removal cost associated with each link is the easiest approach. They then pose the problem of removing *n* links such that the increase in the shortest distance (travel time) between an origin and a destination is maximised given a budget for the removal of links. Jenelius et al.[4] apply similar ideas in a recent vulnerability study of the uncongested, undirected network of northern Sweden. An origin-destination trip (OD) matrix is given for the network. One link at a time is removed from the network and then replaced. For each such removal, some trips cannot reach their destinations (i.e. yielding infinite travel times) or there is a finite increase in total travel time, as the trips that used the removed link are rerouted to find their new fastest routes. Results are presented for all trips as well as for the trips starting from each separate municipality in the study area. These calculations were carried out under the assumption that link travel times are unaffected by the changes in the loads due to the rerouting of the trips. This is quite reasonable for a rural network with almost no congestion. [21] Reykjavík is today on the verge of becoming congested and in the case of removal of certain links the traffic spilling over to alternative routes will result in congestion. For this case it is necessary to apply a network assignment model that allows link travel times to vary with link loads. This increases the computational burden significantly and it is necessary to restrict the analysis to a handful of carefully selected scenarios and therefore it is most cases important to initially conduct a simplified identification process of the most vulnerable links.

6. Measurement of vulnerability

Measuring the vulnerability is not an easy task since there is no definition of vulnerability that is generally agreed upon. Two of the available measures used in previous studies are: (1) generalized travel cost, for the elemental separation between two locations, and (2) the Hansen integral accessibility index [22] which provides an overall measure of the accessibility of one location to a set of other locations. Generalized cost c_{ij} is the overall assessed cost of travel from origin i to destination j in the network. It may be taken as the network travel distance, travel time, the cost or some other measure between the two locations, or as a sum of all of these measures. [3] These two indices are useful in assessing accessibility between major population or activity centers and are thus directly applicable to the study of regional networks such as the road network in the Reykjavík capital area.

In the case of regional analysis involving locations outside major population centers, some other measure of accessibility is needed. Taking generalized cost, it is possible to formulate a basic model that may be used to provide a measure of vulnerability in terms of the change in generalized cost of travel between two locations if a given link fails. The generalized cost may be taken as an appropriate measure of disutility of travel such as distance, time, money, etc – in other words, the increased societal cost from a specific link failure. Generalized cost is seen as a simple measure of accessibility as it indicates the difficulty of traveling between the two locations. [3] By combining the generalized cost together with steady state computer model the overall change in the generalized cost can be calculated and cost can be put on the consequences of the failure of a single link.

In this report vulnerability has as earlier mentioned been defined by using the measure of accessibility, meaning the ease by which individuals from specific locations in a region may participate in activities as for example work, education, shopping and recreation that take place in other physical locations in and around the region and by using a transport system to gain access to those locations. [3] Then vulnerability is defined in the following terms:

- A network node is vulnerable if loss (or substantial degradation) of a small number of links significantly decreases the accessibility of the node, as measured by a standard index of accessibility.

- A network link is critical if loss (or substantial degradation) of the link significantly diminishes the accessibility of the network or of particular nodes, as measured by a standard index of accessibility. [3]

In this study we will mostly concentrate on the links considering that it is the road network and the hazards against it that is analyzed. At a later stage it might also be possible to look at the vulnerability of specific nodes/zones by calculating how much the average trip cost will increase in case that a stochastic link is removed. The standard index that is recommended to be used is based on two different measures, namely the overall increase in travel time and the number of uncompleted trips. When measuring these measures there is a couple of assumptions and decisions that have to be made regarding the travel demand and information.

6.1 Travel demand function

The travel demand function describes how the travel demand changes considering different situations. The easiest function and the travel demand function that is used in this project is inelastic which means that the demand of transport is independent of the time and cost of the transport. [4] This assumption can be assumed since the hazards considered in this study are mainly hazards leading unexpected road closures with relatively short duration. Considering these prerequisites it is unlikely that people will change their decisions to travel or the destinations of their travels since most trips. It is not either especially likely that people will change their mode of travel for short duration closures. The largest changes in the travel demand will instead occur for the choices of route and the departure time.

6.2 Information

In most studies of network vulnerability it has been assumed that the users have perfect information. This means that all users if link is closed it is assumed that all the users of the network will be aware of this at the same time as it happens and when the link is reopened all users will also have access to this information immediately. The users will thus be able to make their choices accordingly. This assumption underestimates the consequences of a closure since in reality the users will not have perfect information and a closure will thus cause larger effects than this scenario. To account for this fact, different methods can be used. For example can a linear information function be used as in [4], to better account for the real costs. However, this is an improvement of the model that might be used in later, but since this study is more comparative the information level model used in this study is that the all users will have perfect information and choose routes based on this.

7. Hazards to the infrastructural road network

This chapter will be a preliminary hazard analysis of the hazards that might affect the capacity of the Reykjavik road infrastructure. There are several different hazards that can decrease the capacity of roads or even shut them of totally. To do this it is good to look at the problem from as many points of views as possible to be able to identify all possible hazards. Thus the first measure will be to divide the hazards into different categories.

There are several different hazards that can cause interruptions in a road city network. In a Swedish study from 1998 [1], the events causing the most interruptions in the Swedish road network were found to be:

1. Road work
2. Floods
3. Traffic accidents
4. Snow problem
5. Blockages caused by storms
6. Accidents with hazardous goods
7. Physical collapses
8. Break of the frost
9. Bridge openings

The order of the hazards would not be the same in Iceland if a similar study was conducted here, considering the differences in climate and in the road network. The list does, however, serve as a good starting point to evaluate the expected impacts of different events by some logical reasoning based on differences between the Sweden and Iceland. The hazards presented in this chapter have been divided into 5 different categories based on the type of event. The 5 different categories are accidents, natural disasters, weather, hazards in the infrastructure itself and deliberate acts to hinder the traffic.

7.1 Accidents

There are a wide range of accidents of different severity and probability that causes disturbances in the road network.

Regular car accidents

Regular car accidents occur quite often and are depending on several different factors such as the speed limits, the traffic and the properties of the road. Thus the probabilities as well as the consequences are different on the different links and it is therefore important to look at every single link to assess the risk at this part.

Probability of regular car accidents

Regular car accident will on most roads be the hazard with the highest probability. In Iceland there is on average 1 car accident per 100.000 driven kilometers. There are, however, large differences between different road sections and thus available statistics from Vegagerðin will be used to create an initial estimation [40].

The probability that 1, 2, 3… accident will happen during a specific number of million kilometers can be described with a Poisson distribution. A Poisson-distribution occurs when the events are independent of each other and might occur at any time. Furthermore, for Poisson-distributed events, it is assumed that they occur with a constant frequency so that on average, λ events occur during a time period t. These conditions can be said to be valid for road accidents. To improve the initial estimation, i.e. the a priori distribution, of λ, the Icelandic statistics are used together with Bayes theorem to create the posterior distribution. To use Bayes theorem, a distribution has to be assigned to the estimated frequency. For Poisson distributed events, a gamma-distribution is suitable since it is conjugated, i.e. the a priori distribution and the posterior distribution are of the same type. [23]

The accident quotas presented in table 3 in Appendix 1 are significantly lower than the quotas calculated from the Icelandic statistics and these statistics are not divided in as many categories either. These differences might be explained with differences in the actual safety levels, since Sweden has one of the safest road networks in the world, but also be a consequence of different ways of collecting data might play an important role. Thus, it would only give a false sense of accuracy to split up the analyzed roads into as many different categories as the Swedish model does. Instead, it was assumed that the Q-value is 0.8 in urban areas and 0.6 in rural areas, independent of the speed and width of the road. The reason for assuming different Q-values for urban and rural areas is because of the differences seen between urban and rural areas in the Swedish model. The estimated Q values were assigned a gamma distribution with a β-value of 10 and consequently an α-value that is the value from the table multiplied with 10, i.e. 6 or 8. The posteriori distribution is a new gamma-distribution with the parameters β+T and α+n where T is the number of million kilometers driven and n is the number of accidents that has occurred during this time [23].

Consequences of regular car accidents

The consequences of a single car accident is, however, most often not especially severe and will not have any widespread effects on the infrastructural road network. Depending on what kind of accident the car is involved it might have somewhat different consequences. Examples of different kinds of accidents are:

- Single accidents
- Frontal collisions
- Queue accidents

The different kinds of accidents do not play an especially important role when assessing the vulnerability of the road network. However, since the energy involved in the different kinds of accidents the disturbances caused by a single accident is likely to be less than those of a frontal collision. When it comes to queue accidents the disturbances might become severe depending if the rescue service are able to reach the accident scene in an easy way or not. In the further vulnerability analysis there will, however, not be any consideration taken to the different kinds of accidents, but the consequences will rather be based on the properties of the links. Instead general distributions of consequence will be assumed depending on the properties of the link. Since there are no Icelandic data available, Swedish data [25] will be used to simulate the time expected time that the road will be blocked. The Swedish data is presented in figure 5. The data can however be represented by lognormal distributions that can be used to in statistical software to simulate the risk. In table 2 the values of the lognormal distributions that are based on the data in figure 5 are presented.

Table 2. Values for the lognormal distributions for the distribution of the duration of a blockage after an accident. [25]

Type of road	Average	Standard deviation
Highway	2.77	0.61
Multiple lanes	2.79	0.49
Regular lanes	2.82	0.53

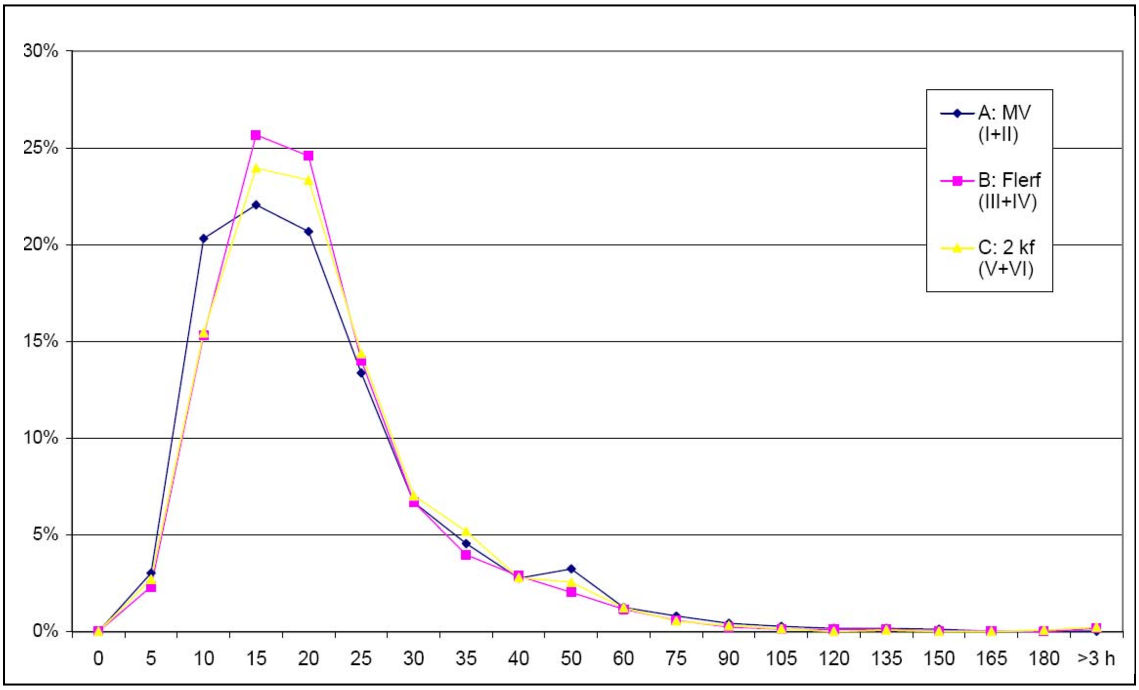

Figure 2. Duration of closures at Swedish roads. [25] (A=Highways, B=Multiple lanes, C=Regular)

Accidents with heavy vehicles

Accidents with heavy vehicles are not as abundant as regular car crashes. This is not especially surprising considering that most of the traffic on the roads consists of regular cars. However, since the probability of a heavy vehicle accident is somewhat different to accidents with regular cars and that effects often become more severe they are treated as separate category of accidents.

Probability of heavy vehicle accidents

The probability of heavy vehicle accidents can be calculated with a model from the Swedish Road Agency (Vägverket) [36] that has been developed for trucks transporting petroleum. According to this model the probability of an accident with a truck transporting petroleum is calculated as:

$$P = N * Q * L * 365 * F * 10^{-6}$$

Where: P = Probability of an accident with a heavy vehicle
N= Number of transports with heavy vehicles in average per day
Q= Accident quota [Number of accidents/million vehicle kilometers]
L= Length of the studied road
F= Number of vehicles involved in each accident

This model might overestimate the probability somewhat since it has been shown in previous studies that the probability per driven kilometer that a professional driver will be involved in an accident is lower than for regular drivers. Thus the risk might be somewhat overestimated but this difference is regarded as negligible for the results of this study.

In a study of the traffic at Reykjanesbraut in 2000 it was estimated that 2 % of the vehicles were heavy vehicles and in the case where no other information is available it will be assumed that this assumption can be applied to other studied roads as well.

Consequences of heavy vehicle accidents

The reason for that the consequences becomes more severe is that it often take longer time to move the heavy vehicle in the case of an accident and there is also a risk that the heavy vehicles drops its load on the road and thus blocks it for a long time. In addition to this an accident with heavy vehicles often create larger damages to the roads themselves because of the larger forces involved in a heavy vehicle accident.

Accidents with hazardous goods

Accidents involving hazardous goods often have the greatest consequences since there is a need for special care when handling vehicles transporting hazardous goods. Thus in most cases it takes extra time before the road is cleared again after an accident with hazardous goods even if the hazardous goods doesn't leak from the truck. Most of the hazardous transports on the Icelandic roads consist of different petroleum transports and in thus it is the consequences of these accidents that will be evaluated.

Probability of a hazardous goods accident

In this study it is assumed that the probability of an accident of hazardous goods can be calculated as the probability of an accident with a heavy vehicle multiplied with the portion of heavy vehicles that carries heavy goods. The probability of a leak in the case of an accident will be based on the Swedish model presented in Appendix 2, but since the classification of Icelandic and Swedish road are not the same a simplified model will be used as presented in [26]. It was assumed that the probability can be represented with linear function where the leakage probability is 0.05 for speed of 50 km/h or less and then increased by 0.05 for every 10 km/h. This assumption gave similar values as the Swedish model for 50, 70 and 90 km/h and can thus be regarded as a fairly good assumption. The leakage probability is presented in table 9 and in figure 7.

Table 3. Leakage probability as a function of the speed limit. (Based on values from [36])

Speed limit (km/h), V	**Leakage probability in the case of an accident, $P_L(0)$**
0-50	0.05
60	0.10
70	0.15
80	0.20
90	0.25

According to Swedish studies [25] the number of vehicles marked as hazardous transports is approximately 1 ‰ of all transports. It was, however estimated that the number of vehicles that might create hazardous goods accident was approximately 1.7 ‰ and this value will be used in the case that there is no Icelandic data available. In the study of the traffic at Reykjanesbraut from 2000 the ADT of oil transports was approximately 0.95 ‰ [27] which is very close to the Swedish values and thus the Swedish value of 1.7 ‰ will be used in this case as well.

Consequences of a hazardous goods accident

The consequences will of a hazardous goods will as mentioned before be in most cases be more severe than a regular heavy vehicle accident because of the increased hazard from the transported substance. In the case that the transported substance starts to leak the consequences will be lot more severe and depending on the properties of the substance the consequence will range from explosions to expensive and time demanding decontamination of the road and adjacent areas. One recent accident with dangerous goods that got large consequences happened in Sweden in November 2005 where a truck transporting gasoline turned over on a highway bridge. In the Swedish accident, it was first estimated that the road would have to be closed for up to six month, but since the northbound part of the bridge was less damaged than expected, a single lane in each direction could be opened just one month later, but even this would have lead to enormous constraints on the Reykjavík road network if it happened at some of its critical links. The repair of the bridge did however take almost a year to complete and the final cost was between 10 and 15 millions SEK [37].

It is also worth mentioning that in the Swedish statistics [1] of interruptions in the road traffic, presented in the beginning of this chapter, hazardous goods accidents were the event that caused the 6th most interruptions. Considering the probability of a hazardous goods accident is significantly lower than for a regular accident, these statistics imply that the consequences of hazardous goods accidents in general are relatively severe and causes large interruptions.

Accidents affecting engineered road structures

The worst scenarios when it comes to accidents on the road are events where engineered road structures such as aqueducts, bridges or tunnels are involved. The reason for this is that a crash into constructions like these might affect the strength of the entire construction and might demand serious repairs during which it may be impossible to use this part of the network.

Probability of an accident affecting engineered road structures

Calculating the probability of an accident affecting engineered road structures is quite difficult since there are a large range of accidents that might affect these kinds of structures. Thus it will be assumed that the probability of accidents is the same along the entire stretch of the link and that a portion of the accidents will affect the engineered structure and this would be calculated as:

$$P = Q * (L_{ES} / L) * C$$

Where:
P = Probability of an accident affecting engineered road structures
Q= Accident quota [Number of accidents/million vehicle kilometers]
L= Length of the studied link
L_{ES}= Length of engineered structures at the studied link
C = Portion of accidents expected to affect engineered road structures (0-1)

Consequences of an accident affecting engineered road structures
Examples of scenarios that might affect the strength of critical constructions are for example cars crashing into fundaments or a petroleum truck catching fire close to an advanced infrastructure. The range of these consequences is very large and can range from few hours of inspection of the structure up to complete closure of the structure for months while repairing or replacing the entire structure.

Accidents in adjacent industries

A fire or an explosion in an adjacent industry might damage the road network in itself. The largest risks are, however, that smoke or gas from the industry might be so thick or dangerous that large part of the infrastructure has to be shut down.

Probability of an accident in adjacent industries

The scenario might seem far-fetched, but an accident of this type actually occurred recently in the Reykjavík area when large amounts of tires were ignited and covered a large of area with smoke and caused the roads in the surroundings to close. It is, however, hard to estimate the exact probability since the probability of an accident in adjacent industries that will affect the road network since there such a wide range of industries and the list of possible scenarios is endless. Thus the probability of accidents in adjacent industries will thus not be calculated but rather just be mentioned as possible hazard.

Consequences of an accident in adjacent industries

The consequences of an accident in adjacent industries are not likely to have effects of long duration on the road network since it will most likely not affect the infrastructure in itself, but it might lead to closures of roads for periods of from an hour up to a couple days in worst case scenarios with fires that are hard to put out or where there is an explosion risk from example gas containers.

7.2 Natural disasters

Earthquakes

Earthquakes happen from now and then in Iceland and even though Reykjavik is not located in one of the most active areas, a large earth quake might have huge effects on the road infrastructure. This has been shown several different occasions before especially in the Kobe earthquake in 1995 where 80 % of the road infrastructure was destroyed and it took years before the infrastructure was working properly again.

Probability of earthquakes

The probability of a large earth-quake hitting Reykjavík is, however not, especially large according to a vulnerability study of earthquakes in southern Iceland. [28]

Consequence of earthquakes

The failure of links in a road network as a consequence of an earthquake is mainly caused by the collapse of neighboring buildings and by collapses of bridges. There are in principal two different causes of damages to these structures namely environmental failure and structural failure. Environmental failure is caused by faulting or liquefaction in the ground. Structural failure on the other hand implies that the damage to the structure because the impact of the earthquake is beyond their designed capacity. Making a difference between the two modes of failures is based on the fact that it has been seen in historical data that almost all units in an area affected by a fault or liquefaction will collapse together. This means that it can be assumed that units affected by the same fault or liquefied area are totally failure dependent, whereas failure from structural failure is more independent.

From historical data, whenever in an earthquake a fault breaks or liquefaction occurs in an area, almost all units in this area will fail together. Also, the probability of environmental failure is higher than the probability of structural failure of the neighbouring buildings and bridges. Therefore, it can be assumed that the units affected by the same fault or liquefied area are totally failure dependent.

Liquefaction is, however, not likely to occur in the Reykjavík area since the prerequisites for liquefaction is high pore water pressures and fine particle clays. [2] Considering the geology in Reykjavík area these conditions are not especially likely anywhere in the studied area. Fault breaks are not either especially probable since an earthquake affecting Reykjavík is supposed to have its epicentre quite far from Reykjavík, thus the main consequences will probably occur because of structural failures.

Volcanic eruptions

The Reykjavík area is just like the rest of Iceland a geologically active area. The number of active volcanoes in the proximity of Reykjavík is, however, very limited. According to the risk analysis for the Reykjavik capital area [33] that there will be a volcanic eruption inside the Reykjavík area, but there might be volcanic eruptions in neighboring areas. This said it shall be remembered that a volcanic eruption can have very widespread consequences affecting huge areas with ashfall.

Probability of volcanic events

Predictions of the probability that a volcanic event will occur is based on historical, prehistoric and geotechnical information. Considering that the number of volcanic events that have been recorded during the historical period when records have been kept, the geotechnical and prehistoric information is very important. [2]

Consequences of volcanic events

The effects of ash fall pose the largest hazards from volcanic events to the Reykjavík road network. The effects of ash fall may not be devastating but far reaching, difficult to remedy and hard to mitigate. In the scenario analysis of possible rescue operations for the capital area of Reykjavík [34] a scenario with a volcanic event at Lönguhlíðar was estimated to give an ash layer over the capital area that was 15 cm on average. This would of course lead to significant consequences in form of for example poor visibility, slippery surfaces and flooding. The main consequence for the road network would however probably be reduced capacity and increased number of accidents because of the poor visibility and the slippery surface.

Tsunamis and high waves

A tsunami is a series of enormous waves created by an underwater disturbance such as for example a volcanic eruption or an earthquake. Areas are at greater risk if they are less than 25 feet above sea level and within a mile of the shoreline. [29]

Probability of a tsunami

A comprehensive study performed by the British Geological Survey in 2005 [30] concluded that the risk of a tsunami affecting the British Isles were unlikely even though there is evidence that this have happened throughout the history.

Considering the origin of the possible tsunamis it was concluded that the probability of a tsunami hitting Reykjavík is lower than for the British Isles. The reason for this conclusion is that Reykjavík is in most scenarios situated further away from the origin or is not expected to be hit directly by a tsunami. When it comes to possible tsunamis originating at the Mid-Atlantic ridge which is situated in the ocean outside of Iceland the conclusion of the British report was that it was unlikely that geological activity in this area would create tsunamis. This is based on the creation of Heimay or previous earth-quakes in the area have created tsunamis, further no tsunami has ever been recorded from mid-ocean ridge anywhere in the world. [30]

Large waves can, however still be created around Iceland and Iceland actually have some of the most violent waves in the world. In the recent history of Reykjavik more than eleven of 5 meters (nautical level) height floods have been recorded. Moreover three extreme floods of ca. 7 meters (nautical level) have occurred in Reykjavik in the last two hundred years. More and more floods may appear in the future due to the sea level rise and consequently such phenomenon must be taken into consideration. [31]

Consequences of a tsunami

The consequences to infrastructural systems can also be catastrophic as was seen in the tsunami that took place in the Indian Ocean in 2004 where the consequences still can be seen several years after the catastrophe. Considering that the entire Reykjavík area is situated at low elevation close the coast in a relatively geologically active area the consequences of a large tsunami hitting Reykjavík would be devastating. Further on a lot of the main roads to and from Reykjavík are localised close to the sea making them extra vulnerable to tsunami events. To even complicate things further a lot of the main roads go on road bridges close to the mouth of rivers which are especially vulnerable to tsunamis. [2]

7.3 Weather

Snow storms

Snow storms are relatively frequent in Iceland and parts of the Icelandic road network are regularly closed for traffic during the winter months because of snow and ice. In the Reykjavík area roads are not likely to be closed for longer periods as a consequence of snow storms, but the travel time often increase significantly because of congestion due to reduced capacity of the roads and accidents. In the concept snow storms all weather with snow or ice causing delays in the traffic network is included.

Probability of snow storms

There are a couple of different methods that could be employed when estimating the probability of snowy weather that will affect the traffic. First of all historical frequency of closures can be used to model the probability of closures. The problems with this that it requires a good record of historical closures of every single road and that the conditions for closing roads have not changed. It is, however, not very likely that this is the case since the methods of clearing the streets have improved and the service expected by the pubic has changed. Thus the reliability based on historical data is quite hard to use. Instead the weather conditions that have lead to road closures can be used as a more reliable parameter since there are more data available regarding the weather than for road closures and this data can also be adjusted to the level of service that is expected today.

Consequences of snow storms

In the Reykjavík capital area it is very unlikely that there will be complete closures of roads as a result of snow storms even if people might be recommended not to use their cars in the case of really bad weather. The capacity of the roads will, however, be severely reduced and the travel time might increase significantly. This might, however, not be too serious since most are likely to assess the information that the travel might increase and thus adjust for it and start there travels earlier. The consequences will also depend on the quantity and quality of equipment that Vegagerðin can provide to reduce the consequences of the snowfall.

Flooding

Evaluating the risks posed to the road network by flooding is not easy, but doing so may reduce the costs of maintaining the network and reduce traffic disruptions that occur as a result of flooding.

Probability of flooding

The probability of flooding that affects the road network can be estimated with different models modeling for example 100 years and look at the consequences that a flow of this size would have. Considering potential climate changes and the change in land use it is difficult to calculate the exact probabilities, but setting up different scenarios based on historical data will still provide a quite accurate picture of the current risk.

Consequences of flooding

Flooding might have very widespread, diverse and severe impacts on the road network. In the Reykjavík capital area there is, however only a limited number of rivers and runoff areas that are likely to be affected by flooding. In the case of flooding the main consequences would consist of damages to roads, removal of roads and blocking of roads by the flood itself or debris Debris will affect the network in two ways during flooding events. First it will act as barriers on roadways that may prevent travel until removed. And second, debris can become lodged against bridge piers which will increase the pressure applied to the piers by the flood waters because of the reduced aerodynamic nature and the increased surface area.

Landslides

Landslides can be triggered by earthquakes, heavy rainfalls and in some cases occur through general instability with no significant trigger event [2]. A thorough analysis of the Icelandic landslide risks was performed in 2006, showing that the hazard within the capital area is quite limited. [32]

Probability of landslides

The probability of landslides is very site dependent and separate probability analysis is needed to be done for all links that are regarded as vulnerable for the road network. The probability of landslides is, however, not especially high considering that the geology in the capital area is not very prone to landslides.

Consequences of landslides

Landslides can have very large consequences if they occur at the wrong places. Two different kinds of consequences can be assumed depending on the where the landslide takes place. In the case of landslide at high elevations where the landslide sweeps down over the road surface the road will be blocked and/or the road surface will be destroyed. In the case of landslides that occur in slopes at the side of the road beneath the road surface the stability of the road will be affected and/or the road surface will be destroyed. Considering the topography of the most likely landslides will be landslides that occur beneath the road surface and even though these landslides are not as spectacular as landslides coming down from hill sides the consequences might be just as large. One good example is the landslide that occurred close to Gothenburg in Sweden in 2007 when 600 meter of the European highway E6 was destroyed in a landslide. E6 is the main route for traffic from Norway down to the continent and had an ADT of approximately 20 000 vehicles. Estimates of the socio-economic costs were that it cost several million SEK every day that the road was closed and the cost of repairing the road was in the size of 100 million SEK. The traffic had to be shifted to small roads with insufficient capacity and a ferry which put a large strain on the people living in the area around the landslide.

Avalanches

Avalanches are high-velocities flow of snow down a mountainside. Considering the large forces involved in avalanches they can have very large consequences to the infrastructure sweeping away and blocking large parts of roads.

Probability of avalanches

Avalanches cause several blockages the Icelandic road network every year and also constitute a hazard to the people travelling on these roads. However, considering that this report only is looking at the vulnerability of the Reykjavík road network the probability occurring at a part of this network is negligible. It is still important to remember the hazards of avalanches in the case that there will be a vulnerability study of the entire road network in the future.

Consequences of avalanches

The consequences of avalanches are similar to those of landslides and will thus not be covered in more detail in this report.

Storms and hurricanes

Storms and hurricanes are in many countries the weather conditions that create the most closures of roads. For example as was shown earlier in this chapter, blockages caused by storms is the event that causes the fifth most delays in Swedish traffic.

Probability of storms and tornadoes

The probability of storms and hurricanes hitting Iceland is relatively high considering its exposed position in the middle of the Atlantic Sea. Severe storms also hit Reykjavík on a regular basis. The latest example was in February 2008 when the wind in Reykjavík was measured to be 24.1 m/s for the 10 minute wind speeds up to 39 m/s in the gusts.

Consequences of storms and hurricanes

Considering the lack of trees in Iceland these weathers don’t have as severe consequences here as at other places. Storms can, however cause disruptions in the traffic, by blowing down different kind of structures and thereby creating blockages in the road network. This will of course have large consequences, but the probability of this happening is a lot lower than for the probability that will blow down. The storm that hit Reykjavík in February 2008 would have had very large consequences in most other countries, but when the storm calmed down the consequences to the road network was mild and the traffic worked pretty much as usual the day after.

7.4 Hazards in the infrastructure itself

Road works

Road works were in the Swedish study the event that caused the most disturbances in the traffic and is likely to have a similar position when it comes to Icelandic conditions. It is therefore of uttermost importance to plan and conduct these works so that they have least impact on the traffic. The probability and the consequences of road works can therefore to a large extent be decreased by good planning and maintenance of the responsible authorities.

Design hazards

If the design of the infrastructure is inappropriate for the conditions that it will operate in, it might fail and thus cause great disturbances on the infrastructural road network. This could for example be roads that are not built for the loads that are subject to and thus deteriorate too fast or bridges where the design loads are too small and therefore will breakdown and be closed for reparations.

Deterioration hazards

Lacking maintenance has caused several serious accidents all over the world that has caused great disturbances to the infrastructure but also resulted in deaths of several people. Within the Reykjavik city area there are no large bridges or tunnels that might cause a catastrophic scenario, however if one of the aqueducts would be closed as a result of lacking maintenance this would have tremendous effects on the travel times for all commuters since there are hardly any spare capacity to be used. Deterioration of roads can also reduce the capacity of the roads and thereby increase the travel time or in the worst case scenario they might have to be closed for a complete restoration.

Failure of other infrastructure

The Reykjavík road network as earlier the only way of land transportation inside the capital area and is therefore crucial for the service of other infrastructural networks. The road network is, however, also subject to hazards from the other infrastructural networks as well. For example if there is a break a water pipe beneath the road the road will most probably be closed for a significant amount of time to fix the leak and change the pipe. In the worst case the entire road has to be closed and the pipe must be dug up from the ground. Hot water pipes have burst on several occasions in Reykjavik, blocking roads or reducing the capacity for significant time period.

Bridges and aqueducts

The vulnerability of bridges is important from a network perspective. In general, because of the high cost associated with building bridges and the terrain they are commonly built in, generally redundancy is less in networks where multiple bridges are required. This means that there in most cases it only exist a few if any alternative routes in the case of a failure of the bridge. The vulnerability of bridges and aqueducts are connected to other hazards and incorporated in other parts of the risk analysis.

7.5 Deliberate acts to hinder the traffic

Deliberate acts to hinder the traffic can have a wide range of reason and consequences and is thus hard to quantify. The probability of such events is also almost impossible to predict and thus the main reasons will just be discussed briefly without any attempt of trying to quantify the risks.

Strikes and protests

Even though strikes and protests are rare phenomenon in Iceland and is more associated with countries in southern Europe they still occur on a regular basis. The protests of the Icelandic truck drivers, in late March 2008, against the Icelandic regulations for truck drivers is just one example that has had a significant impact on the traffic. In this case the blockages have not had especially long duration, but in the case they would like to cause larger impacts they could without too much effort block all traffic in and out of Reykjavík and thereby cut of the city from the rest of the rest of the country. The probability of such an extended scenario is, however, not especially likely due to the intervention of the authorities and negative public opinion. The actions have, however lead to large delays in the traffic and could potentially be dangerous in the case of an emergency.

Sabotage and terrorism

Talking about sabotage and terrorism people most often think about religious extremists and from that perspective Iceland might not be the most likely target. Acts of sabotage and terrorism can, however, be conducted by several other groups or individuals and in the case of the potential targets infrastructural targets often have priorities because of their symbolic value and in the case of Reykjavík they could also have a very large to the entire society.

Warfare

In warfare infrastructural targets are always hit at an early state to take out the opponents possibility to transport supplies and thus there are a couple of links that most certainly would be attacked in the case of war. It is, however impossible to calculate the probability that Iceland will become involved in a war.

8. Design of the Reykjavík's road network

The design of the Reykjavík road network faces some special challenges since Reykjavík is located on a peninsula which means that there are only a limited number of possibilities to get to and from the city. The main routes in the capital area are shown in figure 3 and the numbers are representing the Annual Daily Traffic (ADT) in thousands of trips.

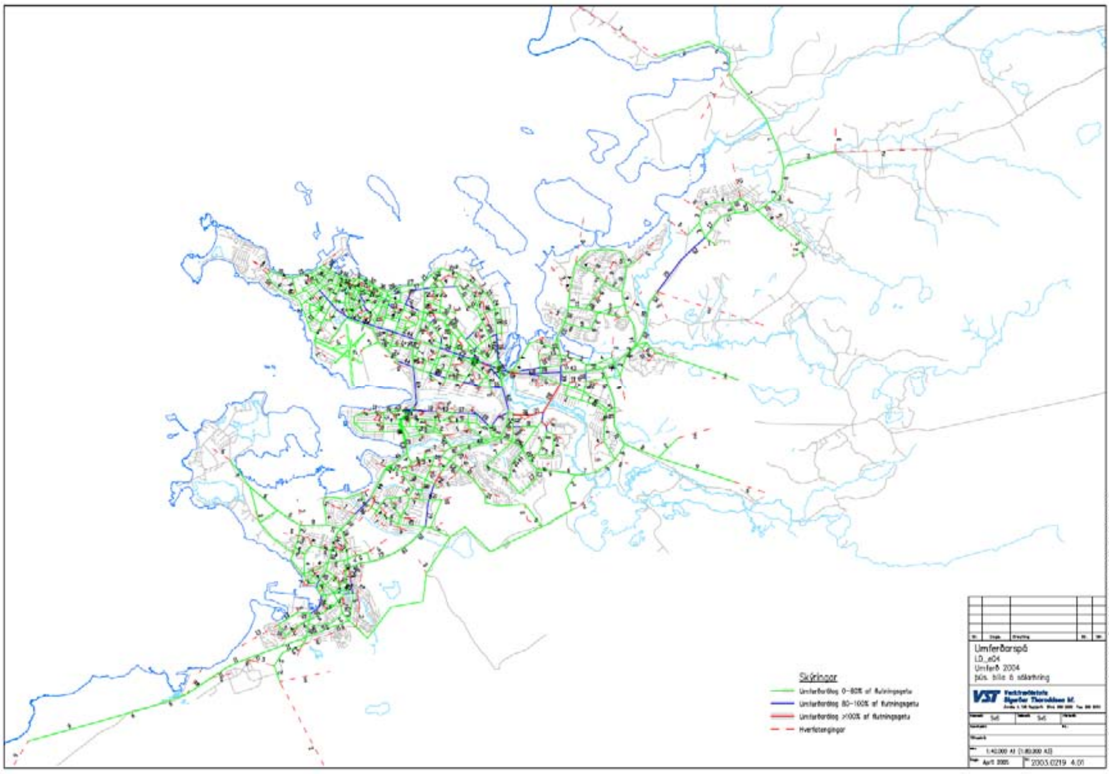

Figure 3. Annual Daily Traffic (ADT) and the capacity useage of the streets in Reykjavík. [24]

8.1 General

The entire Reykjavík capital road network has been set up as a network consisting of nodes of links in the traffic network simulation software CUBE as shown in figures 4 and 5. In the software, the properties of each link have been specified and their capacity is included in the model. Within the program there is also an origin destination matrix that describes not only how many trips per day that are done on each link, but also the starting point and the destination of the travels. Thereby the software can be used to simulate the consequences to the traffic under different conditions.

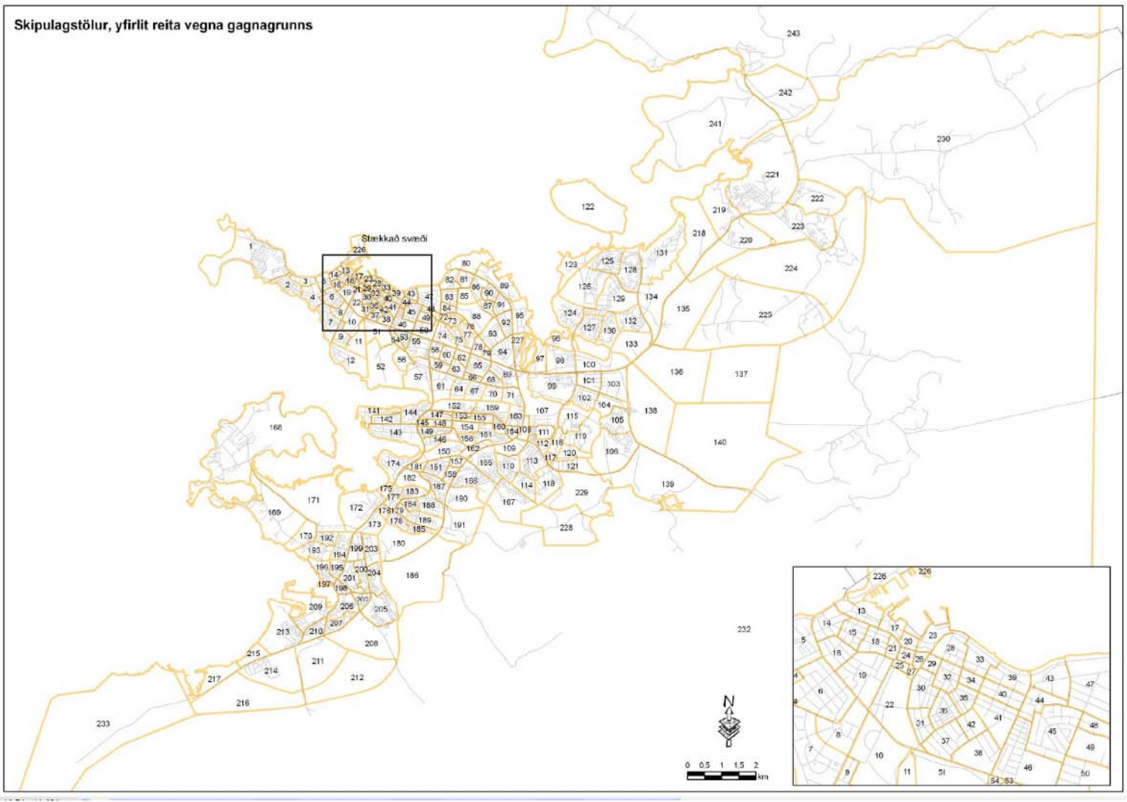

Figure 4. Zones in the Reykjavík road network as modeled in Cube. [24]

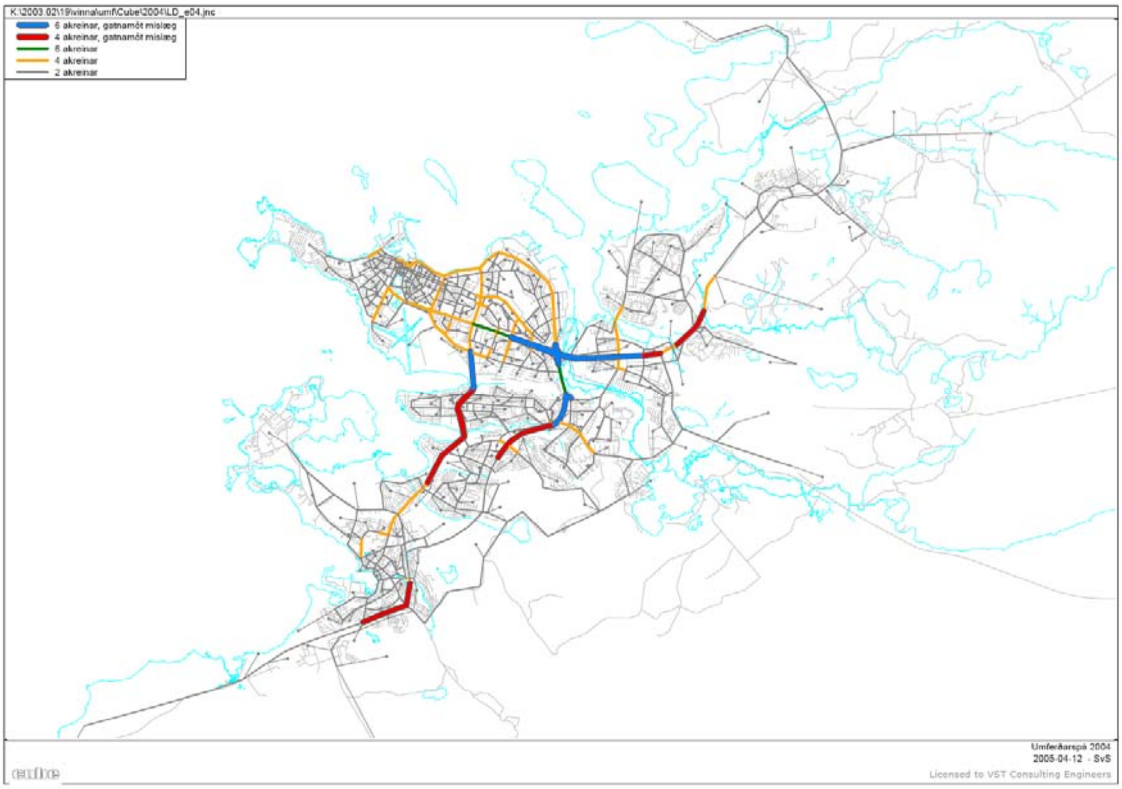

Figure 5. Links in the Reykjavík road network as modeled in Cube. [24]

8.2 Weak spots

Just by visually checking the layout of the Reykjavik road network a couple of weak links can immediately be identified. For example if Kringlumýrarbraut, Vesturlandsvegur and Reykjanesbraut (see Appendix 1) are cut at the wrong places the entire Reykjavík area would become isolated. These roads are also extra vulnerable since parts of them are built as aqueducts or bridges and they are also heavily utilized, both by regular traffic, but also by heavy traffic. On the other hand, all these roads have at least four lanes and at large parts the traffic is separated by barriers making them less vulnerable since it is unlikely that an event will stop all the traffic in both directions.

Figure 6. Layout of the Reykjavík capital area road network, with the main roads marked together with the locations (1, 2 & 3) where pictures in Appendix 1 have been taken. [24]

The three roads mentioned above are the three main routes out from Reykjavík and are therefore among the most vulnerable links seen from a general perspective of the vulnerability. Especially Vesturlandsvegur is vulnerable since it together with Höfðabakki is the only path across Elliðaá and considering that the traffic Höfðabakki already has reached is maximum capacity a closure of Vesturlandsvegur would have a huge impact on the function of the road network.

The report will focus on the vulnerability of these three links since they have such a large impact on the entire network. The consequences will however be hard to estimate since the increase in travel time is not possible to calculate without the software and thus there will only be rough estimations of the consequences and discussion regarding the vulnerability of these links.

9. Discussion regarding the identified vulnerable links

The three different vulnerable links identified in the previous chapter will be discussed based on the hazards that they are subject to. However, hazards, that are expected to have a general effect on the entire network such as snow storms and earthquakes will not be not specifically analyzed, the focus will instead be at the site specific risks. When it comes to the calculations of the accident quotas the Bayesian update approach will not be used on these roads since it won't have any impact on the result considering the large quantity of data that is available for these links.

9.1 Kringlumýrarbraut

Kringlumýrarbraut goes through the center of Reykjavík and continues south towards Keflavík. On its way south Kinglumýrarbraut changes name several times and in the Vegagerðin system, the road is called road 40 or Hafnarfjarðarvegur. In the Vegagerðin accident statistics [40], the road is divided into several parts and the part between Bústaðavegur and Kársnesbraut, which is the only road going across Fossvogsdalur, is in the Vegagerðin statistics represented by the parts Nesbraut(49) - Fossvoglækur and Fossvogslækur - Kópavogslækur. Thus the statistics from both these parts are added together when using the statistics. The part of interest between Bústaðavegur and Kársnesbraut is approximately 1.3 kilometers long (measuring between the actual crossing of the roads and not the ramps) according to measurements in Borgarvefsjá. [39] In figure 7, a picture of the traffic towards Hafnarfjörður at Kringlumýrarbraut, taken from the walking bridge that goes over the road is shown.

Figure 7. View of Kringlumýrarbraut in direction towards Kópavogur. (Location 1)

General traffic

At the critical part of Kringlumýrarbraut, there were, in 2004, an annual daily traffic of 69 000 according to figure 5. However, according to the accident statistics from Vegagerðin the annual daily traffic was between 48900 and 51 300 in 2004 [40]. The difference can be explained by that the data from Vegagerðin considers a larger part of the road and thus the average traffic is lower since there available alternative routes on the other part of the road. In analysis the data material from Vegagerðin will be used since it is more complete and it is also available for a longer time period.

Hazards

The vulnerable part of Kringlumýrarbraut has separated lanes as seen in figure 7 which reduces the risk of serious accidents blocking the road in both directions. The accident scenarios that would cause the largest disturbances in the traffic would be if the Bústaðavegur bridge would collapse and block the road. However considering the design of the bridge with no columns under the bridge makes it unlikely that a regular accident would cause this. The hazard that a vehicle would hit the walking bridge across the Kringlumýrarbraut is more likely, but considering the lighter construction of the walking bridge it would relatively easy to remove it in the case of an accident and open the road again.

There is also a gas station located close to the road, as can be seen in figure 7 which constitutes a significant hazard to the road in the case of a fire or explosion.

Considering the proximity to the sea the hazard of huge waves reaching the road exists and could potentially have large impacts on the traffic. Storms may also constitute a hazard considering the open surroundings around the road, but because of the open surroundings the hazard of debris blocking the road is small. There is not either any specific geological hazard around this part of the road.

Probabilities and frequencies

The frequency of a regular traffic accident at the studied part of Kringlumýrarbraut is according to statistics from Vegagerðin for the years between 2000 and 2004, 1.54 accidents / 1 000 000 driven kilometers [40]. Considering that the annual daily traffic is approximately 50 000 vehicles and the length of the studied road is approximately 1.3 kilometers the expected number of accidents will be approximately 36.5 accidents per year.

Using the assumption 2 % of the vehicles are heavy vehicles would give a frequency of approximately 0.7 accidents with heavy goods every year. The frequency of hazardous goods accident would on the other hand be approximately 0.06 accidents every year and considering probabilities of a leak the frequency of an accident with a resulting leak will be approximately 0.012 since the speed limit at the studied road is 80 km/h.

Other risks have not been quantified at this stage, but possess larg uncertainties.

Consequences

In the case of a an accident affecting the Bústaðavegur bridge there would be very large disturbances to the entire network since it would take several month until the network was put back in working conditions. There is not especially much spare capacity on the alternative routes and the closure would thus have widespread consequences during the entire time until the network was restored.

In the case of a severe regular accident it would in most cases be possible to lead the traffic past accident by using the opposite roadway and have the traffic going in both directions there while the other roadway is cleared and thereby getting the traffic moving again with reduced speed shortly after the accident.

Storms and large waves are not expected to have consequences with long duration but will rather mostly affect the road during the duration of the events and not persist afterwards.

9.2 Vesturlandsvegur

Vesturlandsvegur goes through the center of Reykjavík and is then called Miklabraut. In the Vegagerðin system [40], the road is called road 49 or Nesbraut. In the Vegagerðin accident statistics, the road is divided into several parts and the part between the crossing with Sæbraut/Reykjanesbraut and the ramps of to Bíldshöfði is in the Vegagerðin statistics represented by the part Höfðabakki(419) - Reykjanesbraut(41). The part of interest between the crossing with Reykjanesbraut and the ramps to Bíldshöfði is approximately 0.6 kilometers long (measuring between the actual crossings).

Figure 8. Picture of Vesturlandsvegur in direction towards Reykjavík. (Location 2)

General

At the critical part of Vesturlandsvegur crossing Elliðaá the annual daily traffic in 2004 was 70 000 according vehicles according to figure 5. However, since the statistics from Vegagerðin [40] regarding accidents will be used the ADT used in the calculations will be 71210.

Hazards

The vulnerable part of Vesturlandsvegur has separated lanes as seen in figure 8 and this reduces the risk of serious accidents blocking the road in both directions. The accident scenarios that would cause the largest disturbances in the traffic would be if the bridge over Elliðaá would collapse (see Appendix 1). However considering that there is only little traffic under the bridge and the speed limit is low this is not a very likely scenario, but an accident where hazardous goods are involved could potentially catch fire and make the bridge collapse. Other accidents could also have an impact on the bridge but it is not likely that would be closed for an especially long time period in that case.

Accidents affecting the aqueduct at the crossing Miklabraut/Sæbraut and Vesturlandsvegur/Miklabraut would also create very large consequences since at this intersection is between two of the most trafficked roads in the entire Reykjavík road network and accidents damaging this intersection would have widespread consequences to the entire network.

There is also a gas station located close to the road as well as methane tanking station which constitutes a significant hazard to the road in the case of a fire or explosion at the station. There will also be a methane gas pipe in the ground close to the road as seen in figure 8 which might constitute a hazard in the case of a leak.

The distance from the road to the sea is not especially long and even it is unlikely that a tsunami or a large wave would hit the road it is still possible that such an event could travel up Elliðaá and damage the bridge across the river since it is built to mainly take up forces from the upstream the river. Considering that the bridge crosses Elliðaá there is a risk of flooding that could has the potential to damage the bridge. Flooding could potentially also undermine the foundation of the road causing landslides below the road surface. Storms may also constitute a hazard considering the open surroundings around the road, but because of the open surroundings the hazard of debris blocking the road is small.

Probabilities and frequencies

The frequency of a regular traffic accident at the studied part of Vesturlandsvegur is according to statistics from Vegagerðin, for the years between 2000 and 2004, 1.29 accidents/1 000 000 driven kilometers [40]. Considering that the annual daily traffic is approximately 71 210 vehicles and the length of the studied road is approximately 0.6 kilometers the expected number of accidents will be approximately 20 accidents per year.

Using the assumption 2 % of the vehicles are heavy vehicles would give a frequency of approximately 0.4 accidents with heavy goods every year. The frequency of hazardous goods accident would on the other hand be approximately 0.03 accidents every year and considering probabilities of a leak the frequency of an accident with a resulting leak will be approximately 0.007 since the speed limit at the road is 80 km/h.

Other risks have not been quantified at this stage, but possess large uncertainties.

Consequences

In the case of an accident affecting the bridge over Elliðaá it is likely that only one of the roadways will be affected since the road is built at two separated bridges and in that case the link could still be kept open in both directions on the intact roadway, even if the capacity would be reduced significantly. This is vital since the link over Höfðabakki is already at its capacity limits and in the case that Vesturlandsvegur would be completely closed Höfðabakki would be the only link between the north parts of Reykjavík and the central and south parts of the capital area. There is, however, a hazard in the case of a hazardous goods accident where it is possible that a leak and resulting fire might damage both roadways as in the accident in Halmstad, Sweden where both roadways were damaged after the ignition of petroleum transport. The consequences would be very large for the entire network since there is no spare capacity where traffic could be lead instead.

In the case of a severe regular accident it would also be possible to lead the traffic past accident by using the opposite roadway and have the traffic going in both directions there while the other roadway is cleared and thereby getting the traffic moving again shortly after the accident.

If there would be a large leakage of methane gas or a large fire in the proximity or at the gas station the explosion risk would probably lead to that the entire road would be closed and this could be.

The consequences of events affecting the bridge have already been discussed in the case of accidents and thus consequences of large waves and flooding will not be discussed further here.

9.3 Reykjanesbraut

Reykjanesbraut goes through along the seaside of Reykjavík and is then called Sæbraut and then continues south towards Keflavík. In the Vegagerðin system [40], the road is called road 41 or Reykjanesbraut. In the Vegagerðin accident statistics, the road is divided into several parts and the part between Bústaðavegur and Stekkjarbakki which is beside Kringlumýrarbraut the only south link is in the Vegagerðin statistics represented by the par Nesbraut(49) - Breiðholtsbraut(413). The part of interest between Bústadavegur and Stekkjarbakki is approximately 0.8 meters long (measuring between the actual crossing of the roads and not the ramps) according to measurements in Borgarvefsjá. [39]

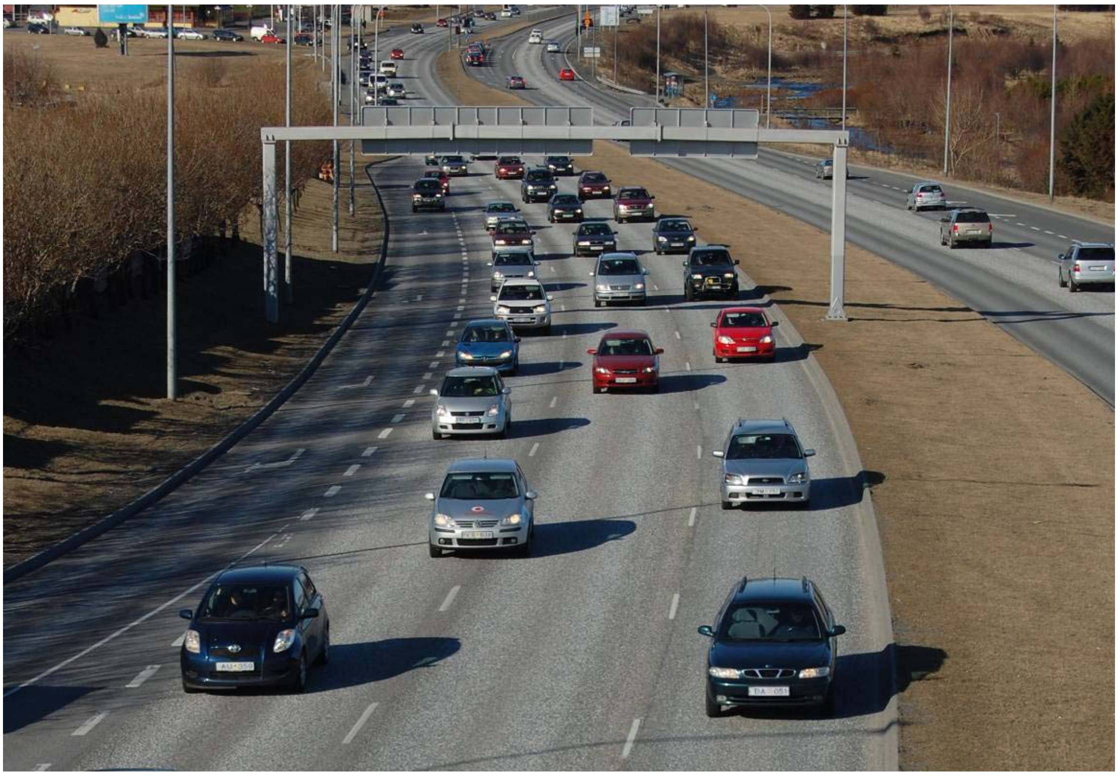

Figure 9. Picture of Reykjanesbraut towards Reykjavík. (Location 3)

General

At the critical part of Reykjanesbraut from Bústadavegur to the crossing Stekkjarbakki the annual daily traffic in 2004 was 62 000 according to figure 5. In the accident statistics from Vegagerðin the ADT is however only 45 600 [40], but as explained earlier this data will be used in this part of the analysis.

Hazards

The vulnerable part of Reykjanesbraut has separated lanes as seen in figure 9 and there are no specific geological hazards around this part of the road.

The scenarios that would cause the largest disturbances in the traffic would be if the Stekkjarbakki bridge would collapse and block the road. Considering the design of the bridge with unprotected columns under the bridge makes it possible that a regular accident would cause large damages enough to at least stop the traffic at the bridge causing large disruptions in the traffic. The hazard that a vehicle would hit the walking bridge across Reykjanesbraut is also possible considering that it has a similar design, but considering the lighter construction of the walking bridge it would relatively easy to remove it in the case of an accident and open the road again. The walking bridges in themselves have little or no impact on the performance of the road network and the consequences would thus not be too large.

Probabilities and frequencies

The frequency of a regular traffic accident at the studied part of Reykjanesbraut is according to statistics from Vegagerðin, for the years between 2000 and 2004, 5.75 accidents/1 000 000 driven kilometers.[40] Considering that the annual daily traffic is approximately 45 000 vehicles and the length of the studied road is approximately 0.8 kilometers the expected number of accidents will be approximately 75.5 accidents per year.

Using the assumption 2 % of the vehicles are heavy vehicles would give a frequency of approximately 1.5 accidents with heavy goods every year. The frequency of hazardous goods accident would on the other hand be approximately 0.13 accidents every year and considering probabilities of a leak the frequency of an accident with a resulting leak will be approximately 0.026 since the speed limit at the studied part of the road is 80 km/h.

Other risks have not been quantified at this stage, but possess larger uncertainties.

Consequences

In the case of a an accident affecting the Stekkjarbakki bridge there would be very large disturbances to the entire network since it would take several months until the network was put back in working conditions. There is not especially much spare capacity on the alternative routes and the closure would thus have widespread consequences during the entire time until the network was restored.

In the case of a severe regular accident it would in most cases be possible to lead the traffic past accident by using the opposite roadway and have the traffic going in both directions there while the other roadway is cleared and thereby getting the traffic moving again with reduced speed shortly after the accident.

10. Conclusion

This study has outlined a method that makes it possible to identify the critical parts of a road network and a way of measuring this vulnerability. This study has further shown that there is a wide range of hazards that might have a negative impact on the road network in the Reykjavík capital area. The consequences of these hazards range from partial blockages of the roads for a number of minutes up to complete closure for several months in worst case scenarios.

The study also points to that it is of large importance to reduce the risks at these links or to increase the redundancy, since the consequences of a failure of these links might can be regarded as unacceptable. A worst case scenario, where all these three links were blocked, could potentially block all traffic to and from the city center. This is not only critical for the use of the road network itself and the trips made at the roads, but also for the service that the road network provides in the case of problems at other infrastructural networks. Since the road network is the only mean of land transportation in and out of Reykjavík the failure of critical links might be devastating.

It is therefore important to consider the total risk and the reduction of the vulnerability. Installing more links would increase the redundancy and since most of the identified hazards are local risks that only will have an impact on a single link the overall vulnerability of the network would be decreased. Considering the low redundancy that exists in the current network, it is of large importance to make sure that these links are resilient enough to withstand hazards with potential large consequences, such as large earthquakes and protecting bridges and aqueducts from being affected by traffic accidents.

The methodology presented in this report can be an important tool and have an impact on the way prioritization of future road projects as well as changes of the current road network if it is used in the right way. The methodology would for example be useful when evaluating the effects on the networks vulnerability in the case of large infrastructural constructions such as for example Sundabraut. There are, however, a couple of areas where there is a need of refinements, especially when it comes to the probabilities of some of the hazards. Because even if there have been quite a lot studies performed regarding the existing risks in Iceland there are still significantly areas of the risk map that still is unexplored. Thus there is need for further studies of certain hazards as well as the ability of certain parts of the infrastructure such as bridges to withstand expected and unexpected events.

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Appendices

Appendix 1 – Pictures of the identified vulnerable links.

Figure 10. View of Kringlumýrarbraut in direction towards Reykjavík. Bústadarásvegur bridge in the distance (Location 1)

Figure 11. Walking bridge across Kringlumýrarbraut. (Location 1)

Figure 12. Picture of the Vesturlandvegur bridge over Elliðará. (Location 2)

Figure 13. Picture of Vesturlandsvegur in direction towards Mosfellsbær. (Location 2)

Figure 14. Picture of Reykjanesbraut towards Kopavogur. (Location 3)

Figure 15. Picture of the Höfðabakki aqueduct over Reykjanesbraut. (Location 3)

Appendix 2 – Calculation matrix regarding accident quota, fraction single accidents as well as index for hazardous goods accidents in different road environments

Table 4. Matrix for accident quota and the probability of leaks depending on the type of the road. [36]

Urban / Rural area	**Speed limit (km/h)**	**Type of road**	**Accident Quota, Q (Accidents /10^6 km)**	**Probability of leak in the case of an accident, P_u**
Urban area	30	All	1.50	0.01
	50	All	1.20	0.03
	70	Regular road / Motorway	0.80	0.11
		4-lane road/ Highway	0.60	0.13
Rural area	70	Regular road / Motorway	0.80	0.15
		4-lane road / Highway	0.60	0.15
	90	Regular road < 8 m	0.42	0.28
		Regular road > 8 m	0.35	0.28
		Motorway	0.37	0.25
		4-lane road	0.40	0.22
		Highway	0.32	0.34
	110	Regular road < 8 m	0.21	0.41
		Regular road > 8 m	0.30	0.34
		Regular road / Motorway	0.28	0.34
		Highway	0.26	0.42