Bachelorproject: 'GIS-analysis centrality of cities'

Dutch road network vulnerability: a trend analysis of networks between 1848 and 2007

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Summary

Roads are essential for the welfare of a country, providing its inhabitants with the means for transportation. Because of this reason there has been quite some research into the vulnerability of current road networks. This research aims to add to this field by providing a method for analyzing road network vulnerability by using historical maps in order to provide a frame of reference for future Dutch road network vulnerability. We can create historical road network datasets in ArcGIS by superimposing lines on the roads of the georeferenced historical reference map. These lines represent the roads of the road network and carry attributes such as road type, traverse speed, length and traverse time. With the aid of the New Network Dataset wizard in ArcGIS we can convert these lines into functioning network datasets by creating junctions where lines intersect. Road network vulnerability consists of three elements: susceptibility of road elements to incidents, amount of users normally using the road element and the increased travel cost for not being able to use a road element. Because there is no data available of road accidents before 1970 it is impossible to incorporate the susceptibility of road elements to incidents. By calculating the betweenness value of each road segment we can approximate the amount of users. Betweenness sums the amount of times a road segment is part of the shortest route between all the different origins and destinations within the network. For the purpose of the analysis we assume that roads that are more often part of the shortest path have more users. Increased travel cost can be calculated within the historical network datasets by recalculating the difference in travel times after the removal of road segment in question. The method was not implemented because it would require the calculation of 259.127.000.000 routes in the year 1848 alone, resulting in an unreasonable computation time of 150 days. Because we were only able to approximate the number of road users, we cannot conclusively describe the vulnerability of the Dutch historical road networks. By visually inspecting the road usage maps, we can observe a clear trend in the distribution of roads users in the historical road networks and propose how this influenced vulnerability. The early road networks had little travel speed difference between roads allowing for a dispersed usage of roads. By 1948 the introduction of highways resulted in a clustering of users on the quicker highways. Towards 2007 this clustering starts dispersing again because of the introduction of more highways, allowing for more alternative quick routes. This clustering on the early highways resulted in a vulnerable network compared to the 1848 situation because of limited alternative routes and the high amount of users that would be impacted by an incident on those highways. The addition of new highways towards 2007 has resulted in a less vulnerable network by dispersing the users and providing alternative routes. However, users are still more clustered then in 1848 and have less alternatives, resulting in increased vulnerability.

Contents

Introduction.

Background

Roads are essential for providing people, companies and institutions around the world with possibilities for transportation. The Romans realized this fact in an early stage of history and responded to this knowledge by building the famous roman *Viae* that connected all of the Roman Empire, providing the means to move armies, trade and bureaucracy throughout the region and creating an era of stability and prosperity (Wiseman, 1970). The importance of transportation and therefore roads in a modern prosperous society like the Netherlands has not decreased, some would even argue that the transportation of goods, people and information across regions is now more important than ever (Banister & Berechman 2003). However, the smooth continuation of transportation over constructed roads is by no means guaranteed, roads can be reduced in functionality or completely stop to function by for example extreme weather and collapsing bridges but also by more trivial things like road accidents and maintenance. The resulting situations can inflict serious costs on the users of the road network such as: Increases in travel times combined with other costs such as increased fuel consumption, disrupted just in time deliveries (Berdica 2002) or a complete inability to access certain regions. With such a large interests vested in the steady continuation of transport, it's no small wonder that there has been quite a lot of research concerned with the vulnerability of road networks. Most of this research focusses on operationalizing indicators for road vulnerability and using it to assess vulnerability in the most extensive and detailed data set available to them. This kind of research allows us to identify weaknesses in our current network, and provides a basis for future improvements. With the focus on the present and the future, one aspect of road network vulnerability is often overlooked: the past. This research will try to create a historical context for our current state of Dutch road networks by analyzing historical maps from 1848 to 2007 and using modern geographic information software to calculate the vulnerability of roads in them. Our goal is to provide a trend analysis spanning the course of these maps so we can put current vulnerability developments in a broader context. Besides providing contextual information for future decisions, this research aims to provide a simple method of analysis for road network vulnerability in maps with limited network information such as historical maps.

Research problem

Main question: How has the vulnerability of Dutch road networks developed between 1848 and 2007?

From this main question stem the following sub-questions.

- How can we create functioning network datasets based on historical maps?
- How can we measure vulnerability in network datasets based on historical maps?
- What are the trends in the of road vulnerability between the years of 1848 and 2007?

Theoretic Frame work

Road usage

Roads are means to achieving our goals of faster transportation and creating a competitive market economy (Roth 1996). In order to approximate the vulnerability of Dutch historical road networks, we will use ideas from economic sociology and the travel time model. The economic perspective allows us to build a simplified model of reality by which we can approximate real life behavior (Swedberg, 2009). We assume the actors in our model are economic men. The economic man is rational, self-interested and strives to obtain the highest possible utility (Rittenberg, 2009). For the purpose of our research the highest utility in road usage is the quickest travel time between origin and destination.

The travel time model demonstrates how travel times are affected by a road incidents and road closure (Jenelius, 2009). The model is based on several assumptions that in combination predict the effect of a road closure on the expected travel time. The first assumption resembles the ideas of the economic man by stating that actors will always follow the path with the lowest travel time cost. Secondly actors are aware of the shortest available routes and the closure of one road does not affect travel time of nearby alternative roads because they have enough carrying capacity to absorb the increased usage. Finally the users also have direct information of any road closure or incident that affects the travel time (Jenelius, 2010). By following the assumptions of the economic man and the travel time model, we can assume that the routes more heavily travelled by are routes that are part of a more of the shortest routes between destinations. Secondly we can assume that the users of a shortest route are capable of accessing alternative routes at an increased travel time. These assumption will lay the groundwork for our measure of vulnerability.

(Road) networks

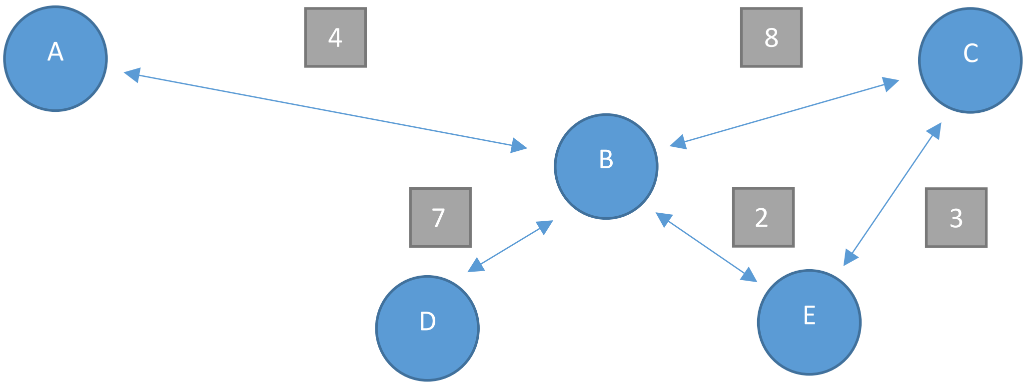
The aforementioned assumption of being able to access alternative routes requires the roads to be connected in a network. There are multiple definitions of (road) networks. Charles Kadushin (2012) a social network researcher defines a network as a set of relationships, or more formally: a network contains a set of objects and a mapping or description of relations between the objects or nodes. Although this definition is more focused on the description of networks we can apply it for our own research by combining it with the definition of Coclite, Garavello and Piccoli (2005). They defined a road network simply as a collection of roads with junctions. Thus the objects and nodes of our network consists of roads and junctions and their relation is that traffic can flow through connected roads and junctions. When we combine these ideas we get the following definition: A road network is a collection of interconnected roads by junctions through which traffic can flow between roads.

The function of these road networks to provide people, companies and institutions around the world with possibilities for transportation. Because economic men will only use the most efficient option roads will have to compete with alternative transport networks like internet, canals and pipelines. If the road network has a reduction in its efficiency of transportation it also incurs a loss in functionality, because if a road network becomes less efficient it's probable that certain transportations will be diverted to other transportation networks or completely halted.

Weighted flow network

Network analysis allows us to describe road networks as graphs representing the relations between nodes. In this research we will approach the road network as a weighted flow network, because it allows us to calculate the least cost routes. A weighted flow network is a directed graph consisting of nodes and arcs. The arcs can only span between two nodes and contains information about the cost or limitations of traveling between the two nodes. In our research the roads will be represented by the arcs, as they span between the junctions and contain the information about the required travel costs or the so called weight. The nodes contain information as to which arcs can be accessed from the respective node. In our research the nodes will represent the road junctions. In graph 1.1 nodes are represented as the blue circles and the arcs as the blue arrows. The cost/weight of traveling with an arc from one node to the other is described in the grey boxes. With this "weighted map" of information we can find the most efficient route from one node to the next by summing the cost of the used arcs. We will apply this concept to make weighted flow networks of the historical maps of 1848 till 2007.

Graph 1.1 Arcs and nodes



Vulnerability

There are multiple definitions of road network vulnerability which each highlight different aspects. (2004) states that vulnerability is a sensitivity to threats and hazards. He implies that the results of such threats and hazards is a reduced ability of the system to maintain its intended function but he does not include it in his definition of vulnerability. His definition thus focusses on the ease of possible exposure to negative events. The definition of Berdica (2002) mentions a quite a similar aspect. Berdica states that vulnerability is a susceptibility to incidents that can result in considerable reductions in road networks serviceability. We can see clear similarities between Berdica's and Holgrem's definition. Both definitions mention the ease at which a network element can be affected. The difference is that Berdica's definition clearly carries a second element, it also mentions the possible impact of an incident as a relevant factor for the vulnerability of a road network. There is a notion of "little strokes fell great oaks" in the concept of vulnerability (Jenelius, et al., 2006). A network element is more vulnerable if the destruction or damaging of such an element can have huge repercussion in the functioning of the network. Earlier on we determined that the function of road networks was twofold: Connecting locations and providing efficient means of transport. The third element we wish to add to our definition of vulnerability is the idea that heavily used parts of the network are more vulnerable. This is because any incident occurring in more used parts of the network influences the utility of more people and therefore has a larger impact on the functionality as a whole. Vulnerability is thus a combination of the amount of actors using a road element, the susceptibility of road elements to incidents and the impact such an event can have on the possibility to connect locations or the efficiency of the connection between locations. In order to quantify the possible impact of an incident within the road network, I have attempted to use three different concepts: betweenness centrality to approximate the amount of users affected by an incident, increased travel time to calculate how the travel times within the network are affected by the removal of a road element and redundancy, a measure of how many times more routes become available if we increase the allowed travel cost by X.

Betweenness

In order to estimate the impact of a reduction in functionality of a road segment we must first know how many people use the aforementioned road segment. Because our historical maps contain no information about road usage we will try to estimate the road usage by calculating the betweenness of roads. Betweenness was originally thought up by Linton Freeman in order to analyze social networks. Betweenness centrality is an indicator of a node's centrality in a network. It indicates how many time the shortest paths from all nodes to all nodes passes through a node (Freeman 1977). Even tough Linton Freeman originally did not develop the indicator with road networks in mind, it is easily applicable in our road networks by measuring the betweenness of the arcs (roads) instead of the nodes (junctions). For the purpose of our research we will assume all road users are homo economicus who have perfect information and pursue their ends optimally by minimizing their costs and maximizing their profit (Henrich et al., 2001). By calculating the betweenness of a road we know how many shortest routes cross that road. Using this information we can approximate the amount of users by assuming that roads that are more often part of the shortest routes are used by more users. For our analysis we will use every road as a point of origin and destination. The betweenness centrality of a road v Is given by the expression:

$$g(v) = \sum_{s \neq v \neq t} \frac{\sigma_{st}(v)}{\sigma_{st}}$$

Where σ_{st} is the total number of shortest paths from road s to road t and $\sigma_{st}(v)$is the number of those paths that pass through v (Freeman 1977).

Impact

The impact an incident has on the functionality of the road network is essential for the measure of vulnerability. The function of road networks is to provide people, companies and institutions with efficient possibilities for transportation. For the purpose of this research two different methods of measuring the impact of an incident on the functionality of a road network were attempted: increased travel time and alternative routes.

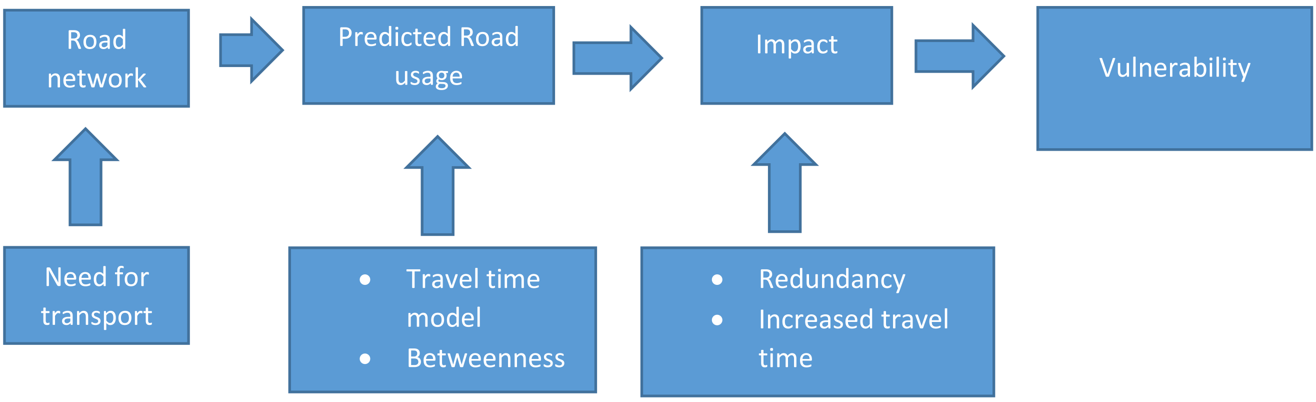
Increased travel time

Increased travel time measures the increased travel time of all routes crossing a road element after the road element was removed. We defined the utility of road networks as the amount of time spent on transportation. A bigger increase in the travel time would result in a bigger decrease in the functionality of a road network. Therefore, a bigger increase in travel time would have a bigger impact. Increased travel time can be measured by recalculating all routes affected by the removal of a road element and comparing their travel time to the previously available route. Because we use the travel time model we assume every user will use the best alternative to the previously available route.

Redundancy

Redundancy is a measure of how many times more routes become available if we increase the allowed travel costs by X. If a road segment of a route can be replaced by a parallel road that is just a little bit more costly we can conclude that the reduction in functionality of the original road segment bears little consequence to the functionality of the road network since it can easily be replaced. By calculating how much alternative routes become available by increasing the allowed for cost from the minimum to slightly above the minimum we can estimate how easily the road can be replaced.

Graph 1.2 Conceptual model



Methodology

The logical starting point for our methodology is the secondary data we were provided with by Dirk Stelder. Stelder is a professor at the faculty of Economics and Business at the University of Groningen, with an expertise in spatial economics, agglomeration modelling, input-output analysis and geographical information systems. The data we were given was initially acquired for a follow up study of his 2014 publication of Regional Accessibility Trend in Europe: Road Infrastructure, 1957-2012. The method chosen for his data creation was a result of a lack of readily available historical road network datasets. The only readily available datasets are from the archives of the Ministry of Transport and were successfully used by Rietveld and Bruisma (1998) to study highway development in the Netherlands. The problem with this datasets is that it only goes back to the year 1970.

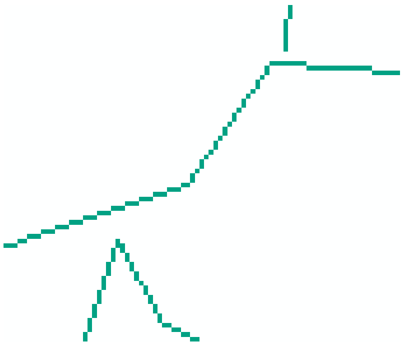
The absence of privately or publicly owned readily available network datasets forced Stelder to produce his own. The only continuously available data of the years between 1800 and the present are old physical road maps, which meant those would have to be the basis of his network. The maps needed to have a clear distinction of road types, be accurate and span the entirety of the Netherlands. The first part of the process consisted of finding, digitalizing and georeferencing physical maps for the years: 1848, 1896, 1931, 1948, 1961, 1971, 1981, 2001 and 2007. By manually drawing vectors of the relevant roads superimposed on the reference maps Stelder was able to create the basis for a road network dataset. The vectors contained information about the road type, the possible car speed on the road and the length of the road. The road speeds were created arbitrarily based on the expectations of possible speeds on the described type of road. The superimposed vectors were provided to us, so we could create functional network datasets with them.

Network creation

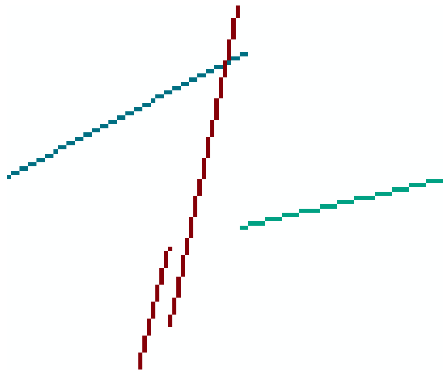
Connectivity

The vectors are created by manually drawing the vectors on top of the reference layer. This presented problems for the connectivity of the vectors. Not all vectors connected properly to one another where the real world road equivalents would have done so. Some vectors fall short of their real live junction and other overshoot the junction and thus create a new dead end. Some vectors pass each other parallel where they actually should be connected.

Picture 1.1 Vectors falling short

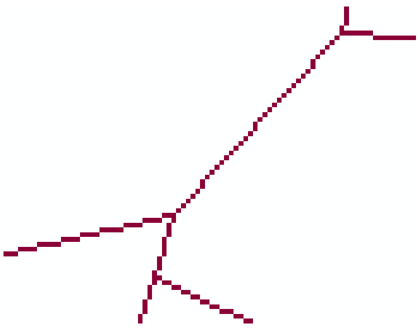


Picture 1.2 Vectors overshooting /parallel

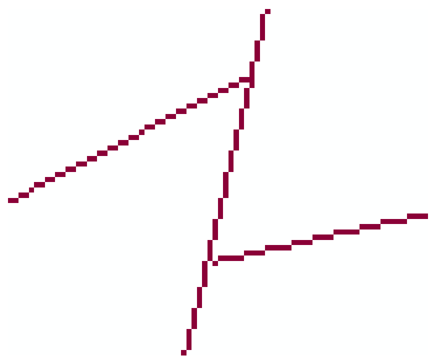


In order to compensate for these errors in positioning we used the 'snap to' tool provided in ArcGIS. This tool snaps the lines towards the nearest line within the allowed for area. The problem with this tool is that it does not discriminate between roads that should be connected together and roads that just lie really close to one another but are not connected. In order to minimize the potential errors by using this tool we limited the allowed for distance to 250 meters. After this operation there is a small chance that we have connected roads that are not connected in reality. However, visual inspection of the maps showed this problem to be marginal.

Picture 1.3 short falling corrected



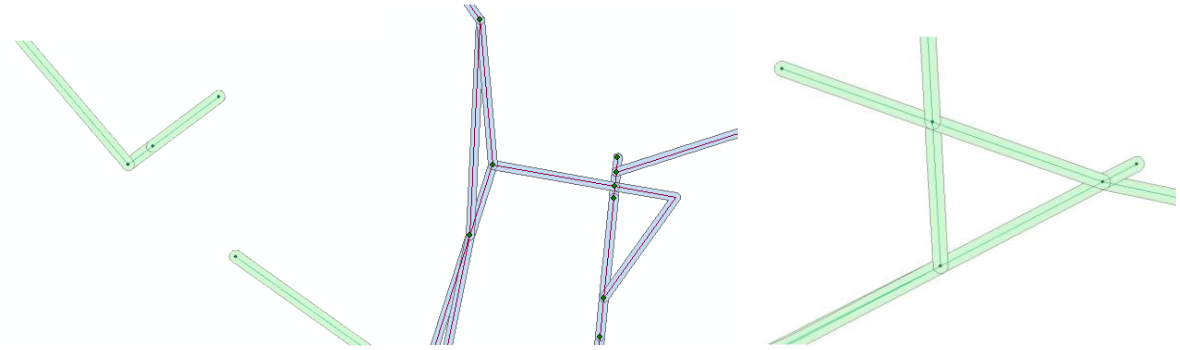
Picture 1.4 Overshooting/ parallel corrected



Unfortunately the snap tool sometimes skipped certain polygons (figure 2.1 A) and could not handle certain shapes of lines (figure 2.1 B), resulting in illogical intersections. In certain cases the snap tool also did not remove the excess length of the lines by snapping back to the point where the lines crossed (figure 2.1 C).

Figure 2.1 A Skipped snap, B incompatible shape, C not removing overshot line.

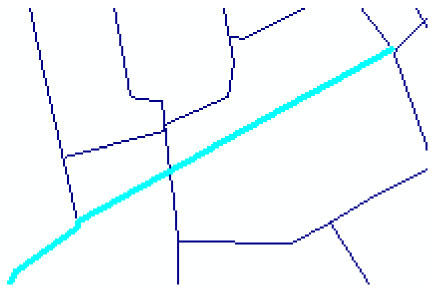
A B C



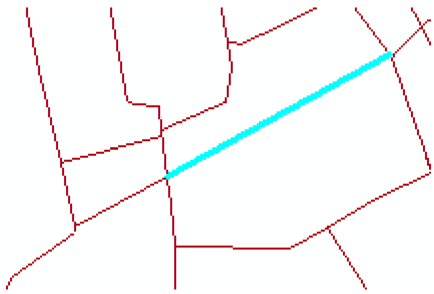
Creating arcs

The next step for creating a functional network dataset is by creating the arcs of our weighted flow network. A weighted flow network is a directed graph consisting of nodes and arcs. The arcs can only span between two nodes and contains information about the cost or limitations of traveling between the two nodes. Earlier on we decided that the nodes of our weighted flow network would consist of the junctions between roads. This means that every road must be split at every junction. When we look at picture 3.1 we can clearly see that this is not the case. The road (arc) passes multiple junctions (nodes). In order to create a functional weighted flow network the road must be split at every intersection. In order to rectify this problem, the 'planarize lines' tool provided in ArcGIS was used, this tool splits selected lines into new features where they intersect. Doing this makes it so that no arc (road) can span more than two nodes (junctions).

Picture 3.1 unplanarized road segment



Picture 3.2 planarized road segment



Travel cost

The definition of the weighted flow network states that arcs contain information about the costs or limitations of travel between two nodes. The cost of traveling along an arc will be based on two factors, the length of a road segment and the expected traverse speed. Because the road networks are based on the historical maps and they do not contain any information as to the possible traverse speed of road segments. We created our own best estimate for each road type in each year. For the purpose of our research we will only be looking at time as a cost for traversing a road segment. The time necessary for traversing an element in hours can easily be calculated by dividing the length of a road segment in kilometers by the expected travel speed of a road segment in kilometers per hour. With the elements of proper connectivity, arcs and travel cost in place we can begin to construct a network geodatabase in ArcGIS. This functionality automatically connect endpoint of arcs to the nearest line by a node. While doing so it can also save the expected travel cost to the arcs allowing us to create a weighted travel network. The network was created using the "New Network Dataset wizard" in ArcGIS. With this tool we can convert the now properly connecting arcs into a functioning network datasets by creating junctions where lines intersect.

Dijkstra algorithm

The possible impact of a network element is decided in part by the betweenness value of the road. (Wang et al. 2012). The betweenness value of an arc (road) depends on the amount of times a shortest route crosses the arc. In order to determine the shortest routes between every point of origin and point destination in the network I will be using the Dijkstra's algorithm. The Dijkstra's algorithm finds the shortest path between two nodes by picking the unvisited nodes with the lowest distance. It then calculates the distance through it to each unvisited neighbor and updates the neighbor's distance if it's smaller. It continuous doing this until there are no longer any unvisited nodes. This algorithm only works when applied to an arbitrary directed graphs with unbounded non-negative weights. Arbitrary directed graphs means that every road can be traversed in both directions for the same travel cost. Unbounded means that the travel cost between two nodes cannot be dependent on earlier routes and finally there cannot be negative cost values. The simplistic nature of our network based on old road maps makes it so that our network adheres to these specifications without any modifications. We will be using the Urban Network Analysis Toolbox for the computation of shortest routes and the betweenness values. For the points of origin and destination we use every road within the network.

Increased travel time

Increased travel time measures the increased travel time of all routes crossing a road element after the road element was removed. Increased travel time can be measured by recalculating all routes affected by the removal of a road element and comparing their travel time to the previously available route. The initial and recalculated travel times could be calculated using the Urban Network Analysis Toolbox. For each road segment that is removed we have to recalculate al the affected routes. By summing the betweenness value of each road segment we know how many routes need to be recalculated. For the year 1848 alone 259.127.000.000 needed to be recalculated. Because of the nature of network analysis, the computation of routes takes quite a lot of time. Based on the time required to compute the betweenness, it would take about 150 days to calculate al of the 259.127.000.000 alternative routes. Because of the time requirements this method was dropped.

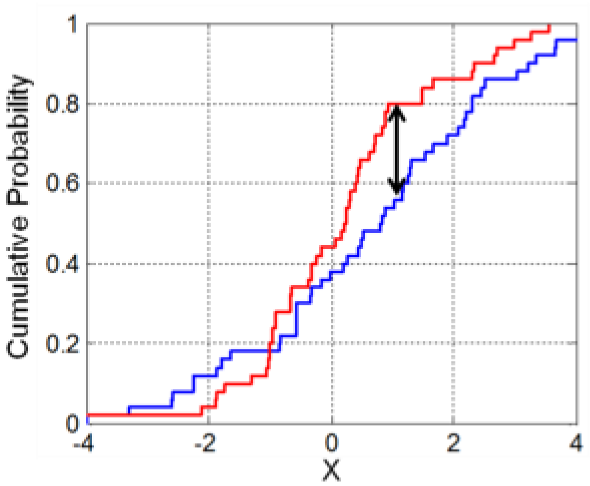
Redundancy index

Redundancy is a measure of how many times more routes become available if we increase the allowed travel costs by X above the minimum. We can calculate this measure using the Urban Network Analysis Toolbox. The limitation of this method is that it cannot use the Dijkstra algorithm. The Dijkstra algorithm is based on the idea of updating the travel cost to nodes with the lowest value. Because we are not only interested in the shortest route our method also needs to take into account less efficient alternatives. Because it needs to calculate more alternative possibilities it requires more computing time. For the purpose of our research the computing time reached such high levels that it was impossible to complete the calculation in time. The method and measure are possible for the purpose of this research, but they were also abandoned because of the time requirements.

Trend analysis Kolmogorov-Smirnov test

The goals of this thesis was to detect a trend in the vulnerability of the Dutch road networks. Because a trend requires a difference between years it's convenient to start with a statistical analysis that proves there's a difference between each year. Because of the nature of the calculation method used for calculating the betweenness of each road element the data is not normally distributed. The mean value of the betweenness is also highly dependent on the amount of origins and destinations. Because we used each road as a point of origin and destination and the amount of roads differ between each year we cannot assume equal means. We can thus only use the Kolmogorov-Smirnov test to compare the distribution of betweenness between each year. This test is a non-parametric test of the equality of continuous one-dimensional probability distribution, which can be used to compare two samples. It calculates if there is a significant difference in the cumulative probability plots between two years (the black arrow in Graph 1.1). The 0 hypothesis of this test is that the two samples are drawn from a source with the same distribution. If the 0 hypothesis is rejected we can conclude that there is a difference in the way the data is distributed. This means the data is clustered differently across roads between years. Such a difference would indicate there is a trend or at least a change in Betweenness between different network years.

Graph 1.1 Cumulative probability plot



Visual inspection

The second method used for analyzing the trend in road vulnerability is a visual analysis of the road networks. By codifying the betweenness as a color ramp and comparing the road networks between years, we can easily spot the concentration of users in the road networks. By also codifying the traverse speed of road segment as a color ramp and comparing the road networks between years, we spot trends in availability of high speed alternatives.

Results

The goal of this thesis was to create a method for analyzing the Dutch historical road network vulnerability trend and by doing so provide a frame of reference for future investigation into the Dutch road network vulnerability. In the following chapter we will discuss the results for each of the sub questions and finish with the results of the main question.

Creation of historical network datasets based on historical maps.

The data provided to us by Stelder proved more than adequate to create functional road network datasets. We were able to create network datasets for the years 1948, 1931, 1948, 1961, 1970, 1981, 2001 and 2007 that were suitable for network analysis. The only year we were not able to convert to a functional road network dataset was the year 1896 because the base level of provided information was very minimal for this year, with only main roads converted to lines and a complete absence of attribute data for each road. The creation of a road networks from lines superimposed on historical reference maps thus seems to be a viable option for creation historical network datasets. This method was previously used by Stelder for his research on the regional accessibility trend in Europe (Stelder, 2014). The nature of the data did require the usage of several ArcGIS tools in order to improve the quality of the data, these tools had mixed results as to how far they were able to compensate for possible errors and created some errors of their own that have small implications for the network analysis.

Developing a method for measuring vulnerability in historical road networks.

By defining vulnerability as a combination of the amount of actors using a road element, the susceptibility of road elements to incidents and the impact such an event can have on the possibility to connect locations or the efficiency of the connection between locations there was a need for three different elements of vulnerability for road elements: susceptibility to incidents, number of users and impact. I was unable to create a measure of susceptibility to incidents because this required data about incidents on road elements for every year and the available data only went back to the year 1970. By calculating the betweenness value of every road element I was able to approximate the amount of users on each road element. For measuring the impact of an incident I attempted two methods: increased travel time and redundancy. Both methods can work with the network dataset but could not be implemented due to the required computation time. Even though I was unable to completely operationalize vulnerability within my network dataset, we can still use the betweenness measure in order to draw preliminary conclusions about vulnerability.

Kolmogorov-Smirnov test

For this thesis two methods were proposed for analyzing the vulnerability between years in order to detect a trend. The first method is the nonparametric Kolmogorov-Smirnov test that allows us to test if the betweenness values between years follow the same distribution. The null hypothesis is that the both sample are drawn from the same distribution. If each year has the same distribution of betweenness it’s highly unlikely that there will have been a shift in road usage between the years because a clustering or decluttering of betweenness would result in a different distribution. Graph 2.1 shows the probability of each year compared to the previous year being drawn from the same distribution.

Graph 2.1 Kolmogorov-Smirnov test between each subsequent year.

YEARS COMPARED	1848-1931	1931-1948	1948-1961	1961-1971	1971-1981	1981-2001	2001-2007
P	,000	,000	,000	,000	,000	,000	,000
TOTAL N	51798	17895	11316	19280	28060	30391	27399

Two sided significance level of 0,05.

As we can see in graph 2.1 the probability of the null hypothesis being correct is 0,000 in every case. We can thus reject the null hypothesis for every year and conclude that each year has a different distribution compared to the previous year. Such a difference between distributions indicates a change or possibly a trend in vulnerability between different network years.

Visual inspection

The second method proposed for detecting a trend in the historical road networks is the visual inspection of maps codified with vulnerability as a color ramp. By analyzing the different years we can try to spot a trend in the distribution of betweenness. Because of the required size and detail for a visual inspection the maps will be presented in the appendix of the thesis. A less detailed overview map (map 2.1) with only the most intensely used road will be presented in the result paragraph for quick comparison.

Map 2.1 Overview map of intensely used roads from 1848 to 2007.

1848

Map 3.1 shows the distribution of road usage in 1848. In map 4.1 we can see that all the roads have the same travel speed because of the speed limitation only being limited by the speed a horse can traverse a road. Even though you would expect a very diffuse spread of road usage because of the easily available alternative routes with the same travel speed, we can spot a clear clustering of road usage on certain central roads. Compared to other years the clustering of users is quite dispersed.

1848-1931

Map 3.2 shows the distribution of road usage in 1931. In this year the roads have different travel speeds, because of the introduction of the automobile. Because this mode of transportation is more sensitive to the quality of the roads different traverse speeds are introduced into the model. This difference in possible speeds reduces the ease at which alternative routes can be found. As A result of this we see a clear clustering of users compared to 1848. By Clustering users on roads the possibility for a high impact incident increases, making the network more vulnerable.

1931-1948

Map 3.3 shows the distribution of road usage in 1948. With the creation of highways, the larger difference in speeds has resulted in a slightly more clustered structure of road usage. Previously we could observe 4 roads with a high road usage in the North of the Netherlands. In map 3.3 we can spot only two of such roads, indicating an even further clustering of road usage along the Dutch road network. This increase in clustering mainly occurs in the North and East of the country. At the same time we can observe a small dispersion of clustering in the South. This further clustering of users results in a possibility for bigger high impact incidents, making the network more vulnerable.

1948-1961

Map 3.4 shows the distribution of road usage in 1961. The distribution of road usage differs very slightly from 1948. Some areas become slightly more dispersed.

1961-1971

Map 3.5 shows the distribution of road usage in 1971. The distribution of road usage divers slightly from 1961. The coast area between North and South Holland becomes less important in terms of road usage. The increased clustering of users in the coastal regions and the South of the Netherlands results in a slight increase in vulnerability.

1971-1981-2001-2007

Maps 3.6, 3.7 and 3.8 show the distribution of road usage in the respective years of 1981, 2001 and 2007. These maps show a reversal of the previously observed trends. Instead of a further clustering of the road usage they demonstrate a further dispersion of road usage. It does not quite approach the old layout of 1848 where the user pattern was more dispersed but it shows clear improvement over the situation in for example 1971. The experienced increase in dispersion can be explained by an increase in High speed roads. When we look at map 4.1, 4.2 and 4.3 we can observe that the initial introduction of highways results in a clustered network compared to 1848. But as we can see in map 4.2 the number of highways rapidly increases resulting in a dispersion of users. This increase in dispersion results in a decrease in road network vulnerability because it provides less opportunity for big impact events.

Conclusions

The goal of this research was to create a method for analyzing road network vulnerability in historical network datasets in order to provide a trend analysis as a reference frame for future research into Dutch road network vulnerability. For the purpose of this research vulnerability was defined as a combination of the amount of actors using a road element, the susceptibility of road elements to incidents and the impact such an event can have on the possibility to connect locations or the efficiency of the connection between locations. With the data provided to us by Stelder we were able to create functional historical network datasets. With this datasets we were only able to create one of the three elements of road network vulnerability, namely the approximation of the number of users. We can still analyze this aspect to produce a context for future road network vulnerability. The distribution of betweenness differs significantly between each year. This means the distribution of the values change between years and we might be able to spot a trend in betweenness. This visual analysis shows a clear trend in the road usage in the Netherlands. From 1848 until 1948 we detect a clear clustering of high use roads. This clustering results in a higher vulnerability of the Dutch road network because increasingly more routes become dependent on a limited amount of road passages for their shortest routes. This clustering increases the possible impact a single road incident can have to larger proportions of users than previously possible. After 1948 the rate of clustering stagnates and the vulnerability remains pretty much as is. After 1971 we can see a reversal in the clustering of high use roads. The routes become more dispersed because more high speed alternatives become available within the network. The results of this dispersion is a lower vulnerability of the network, since a single incident cannot affect the same amount of users all at once. The availability of more high speed alternatives also improves the redundancy of our road network by offering high speed alternatives. Even though the construction of more high speed alternatives creates more dispersion it does not approach the level of dispersion observed in 1848. This means that our current network is still more vulnerable than the original network of 1848. The perspective this offers on future road network vulnerability analysis in the Netherlands is the fact that our vulnerability was decreasing from 1971 to 2007. If future research shows that vulnerability of the Netherlands has reached a stable position it should be interpreted as a negative situation, because it shows an end to a positive trend.

Discussion

The current method for creating historical road network datasets has some limitation in terms of functionality and accuracy. The speeds contained within the network datasets are still rather arbitrary because there was not sufficient data on travel speeds on certain road types. Secondly the datasets do not contain all the ferries operating at the time and assume there is a perfect connection for every potential passenger requiring no time for embarking or disembarking. The datasets also connects overpasses or tunnels that do not connect to overlying or underlying roads in real life. This error results in road network connections that were not there in reality. The way by which the lines were superimposed on the historical reference maps results in the necessity of using the snap to and planarize tool resulting in network inaccuracies such as: connections where there were none in real life or a lack of connection where there was one in real life.

The quality of the historical network datasets could be improved by creating more accurate manually drawn lines on top of the reference maps. A second big improvement to the quality of the road network datasets could be made by finding more sources for accurate estimation of road speeds on different road types. The current sources limit themselves to general road regulation after 1974 and anecdotal evidence obtained from multiple other sources. A third point of possible improvement is by creating a population density attribute for the road elements, based on this attribute the importance of a road element as destination or origination can be determined for future betweenness analysis. The vulnerability analysis can also be further improved by implementing the element of redundancy or increased travel time. In order to create these variables one just needs access to considerable computing power.

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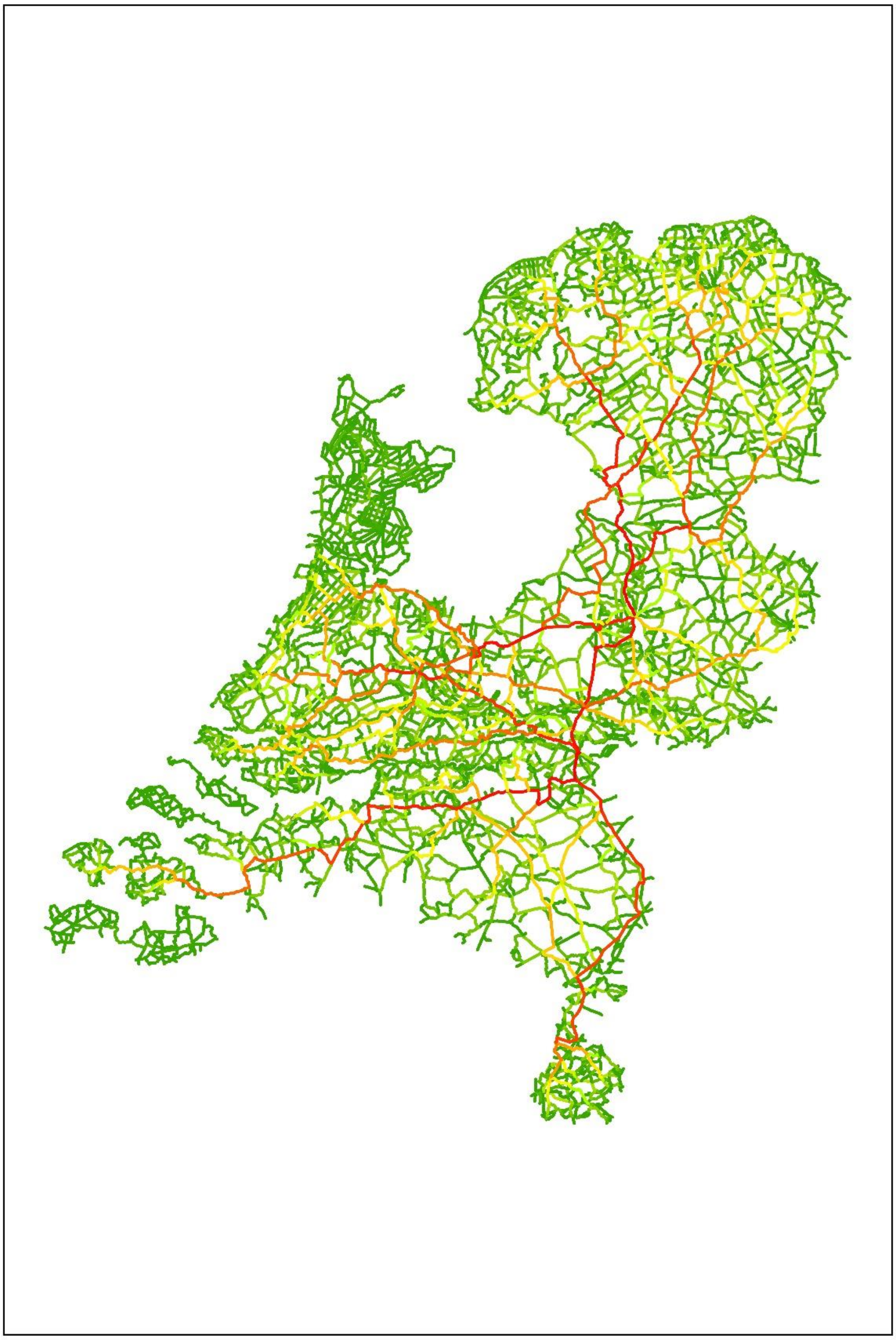
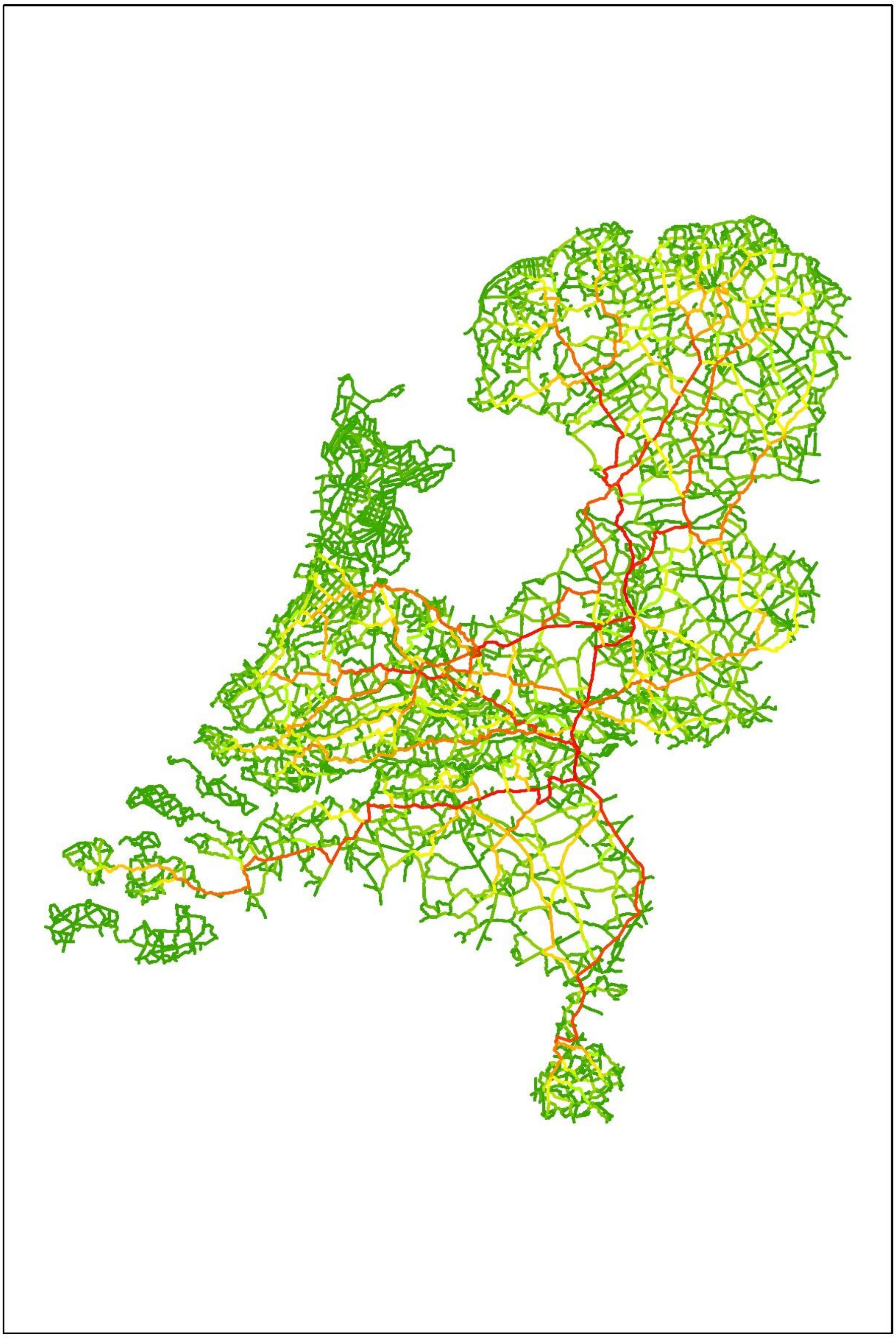
Appendix

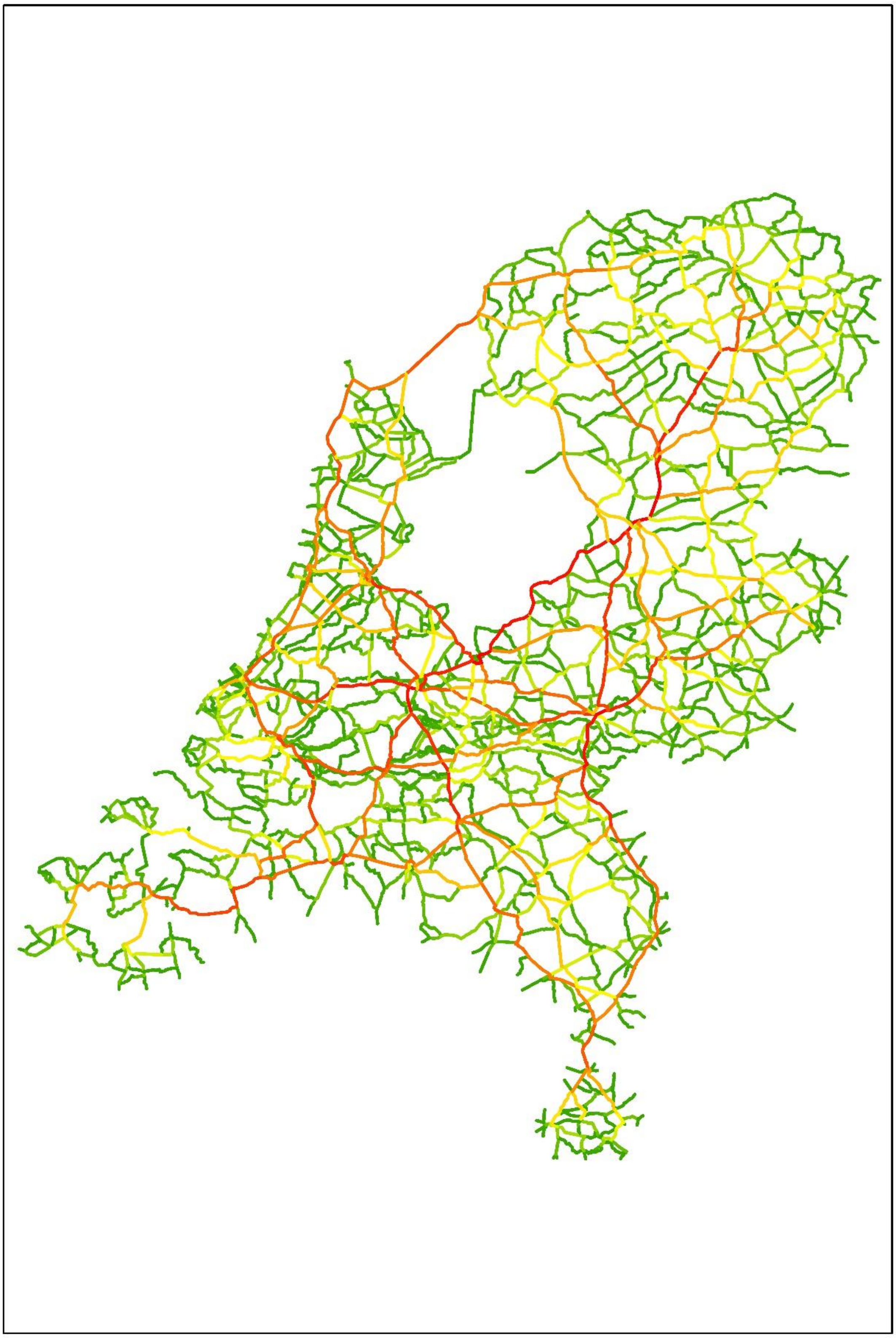
Map 3.1 approximate road usage 1848 based on betweenness



Map 3.2 approximate road usage 1931 based on betweenness

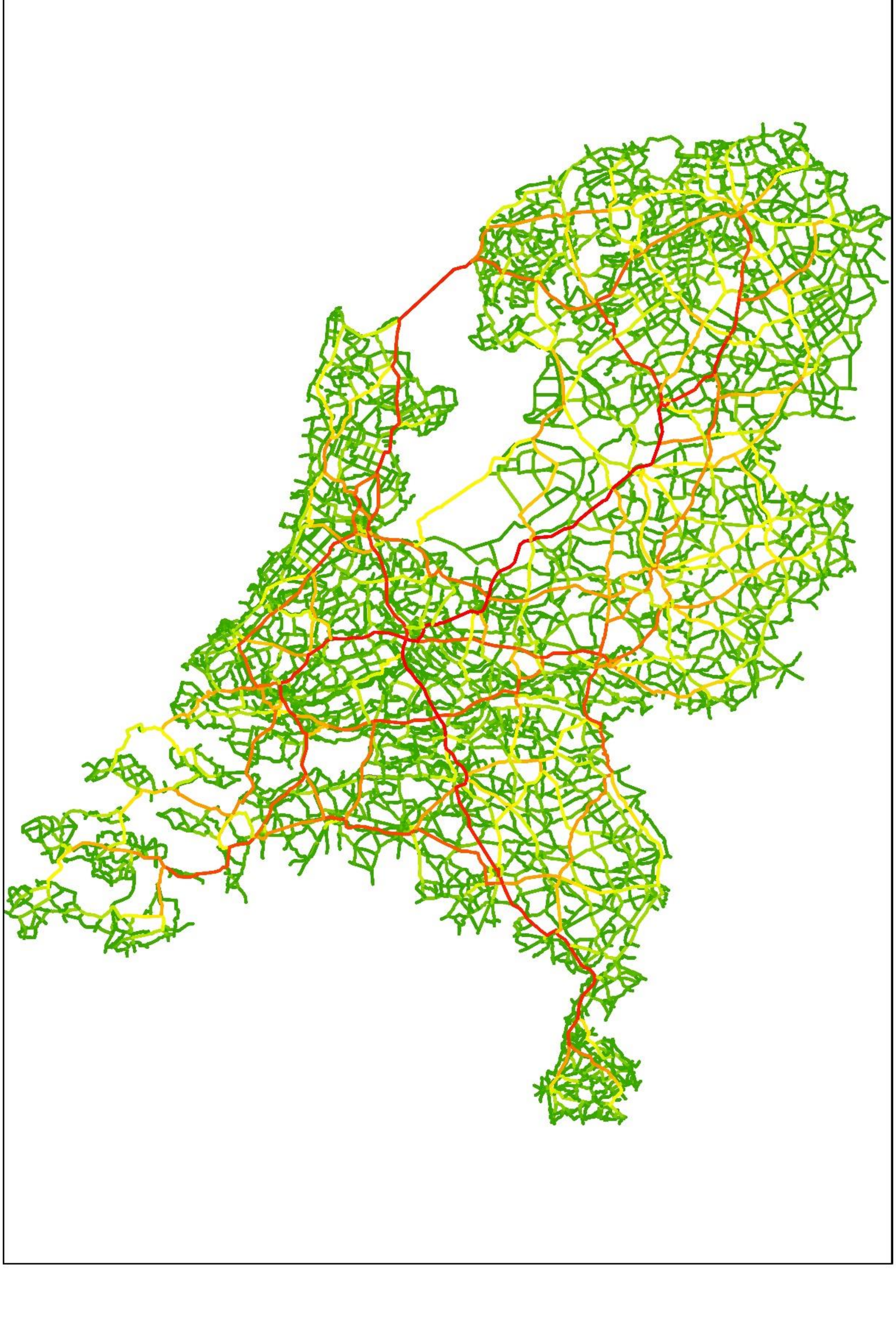


Map 3.3 approximate road usage 1948 based on betweenness

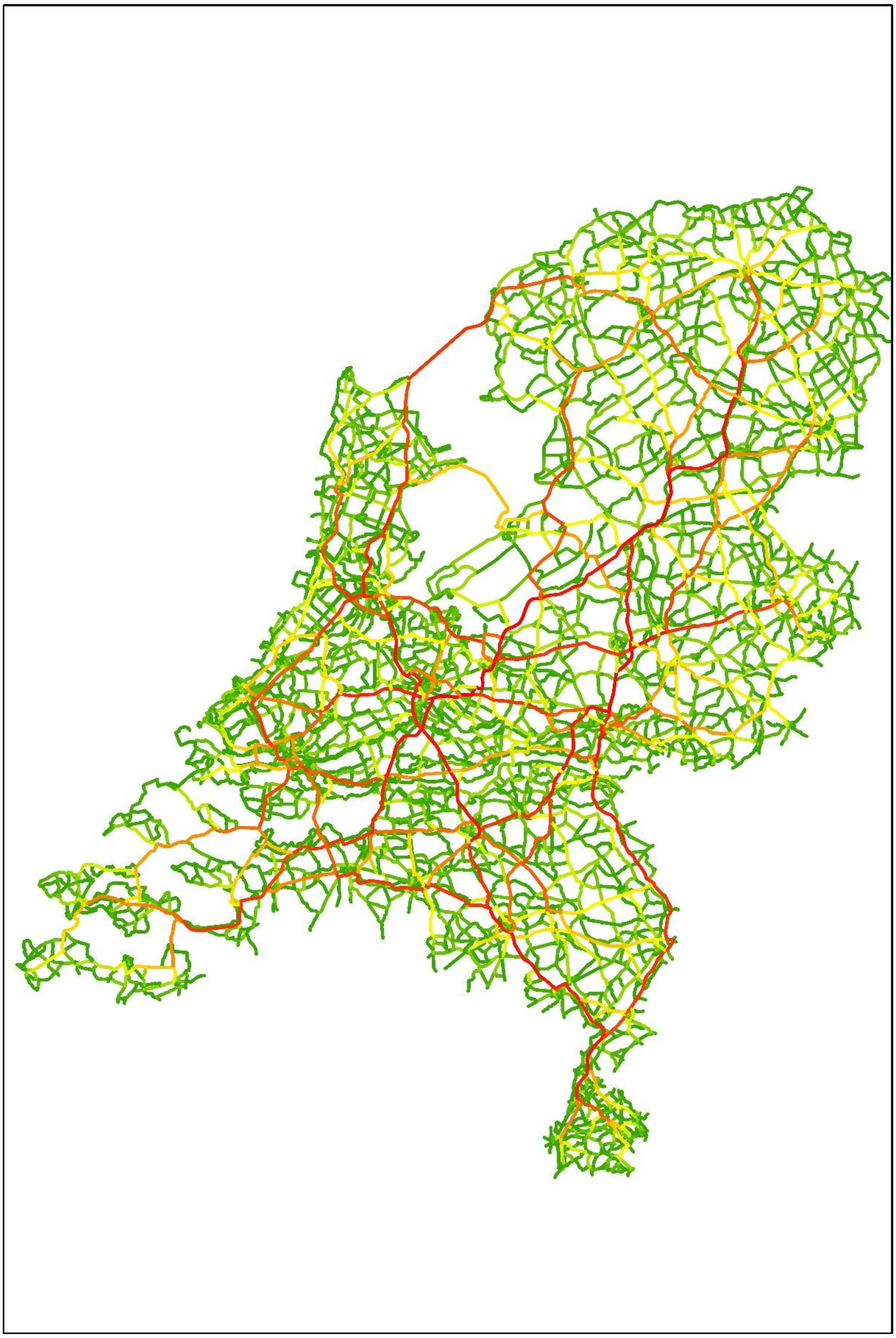


Map 3.4 approximate road usage 1961 based on betweenness

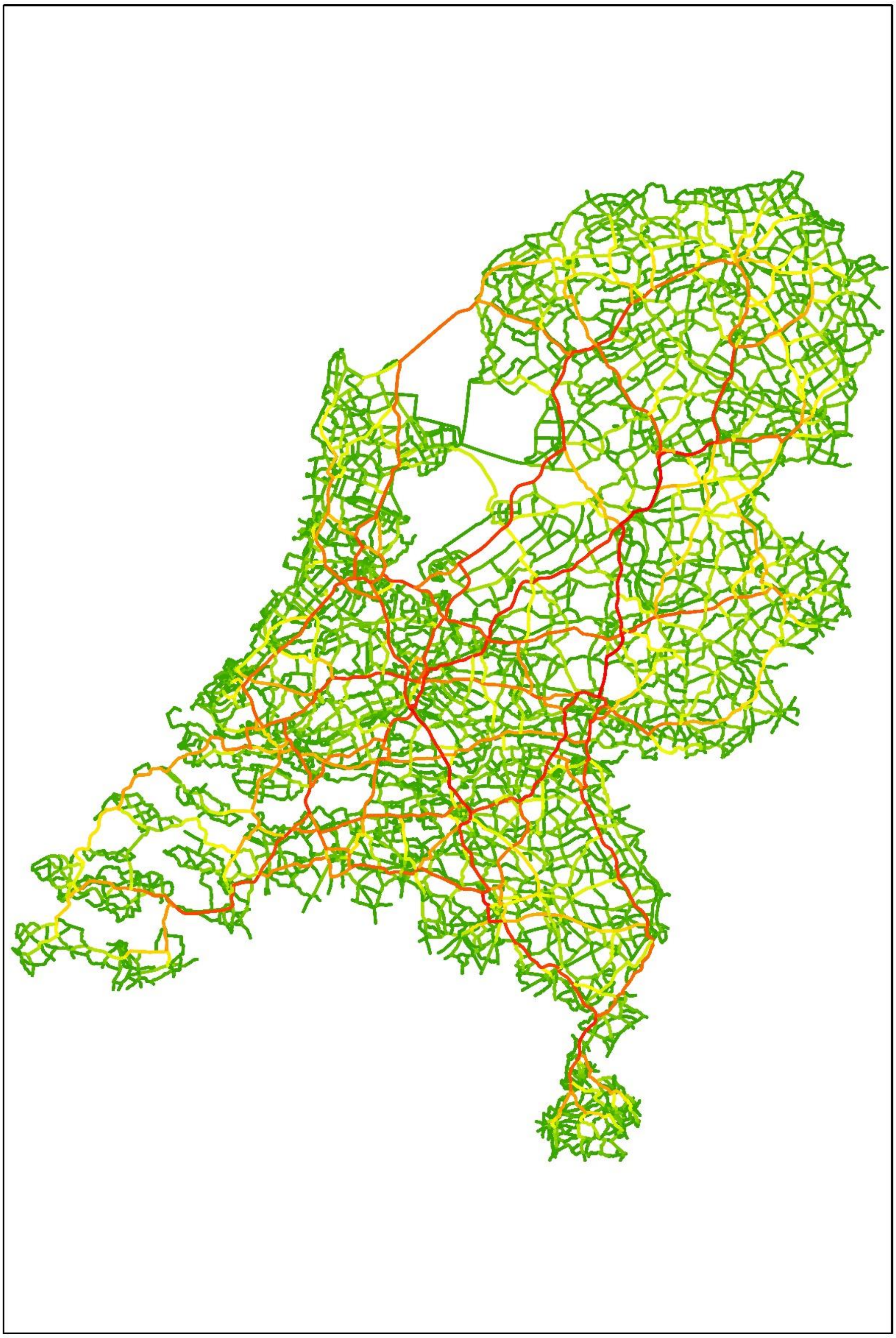
Map 3.5 approximate road usage 1971 based on betweenness



Map 3.6 approximate road usage 1981 based on betweenness

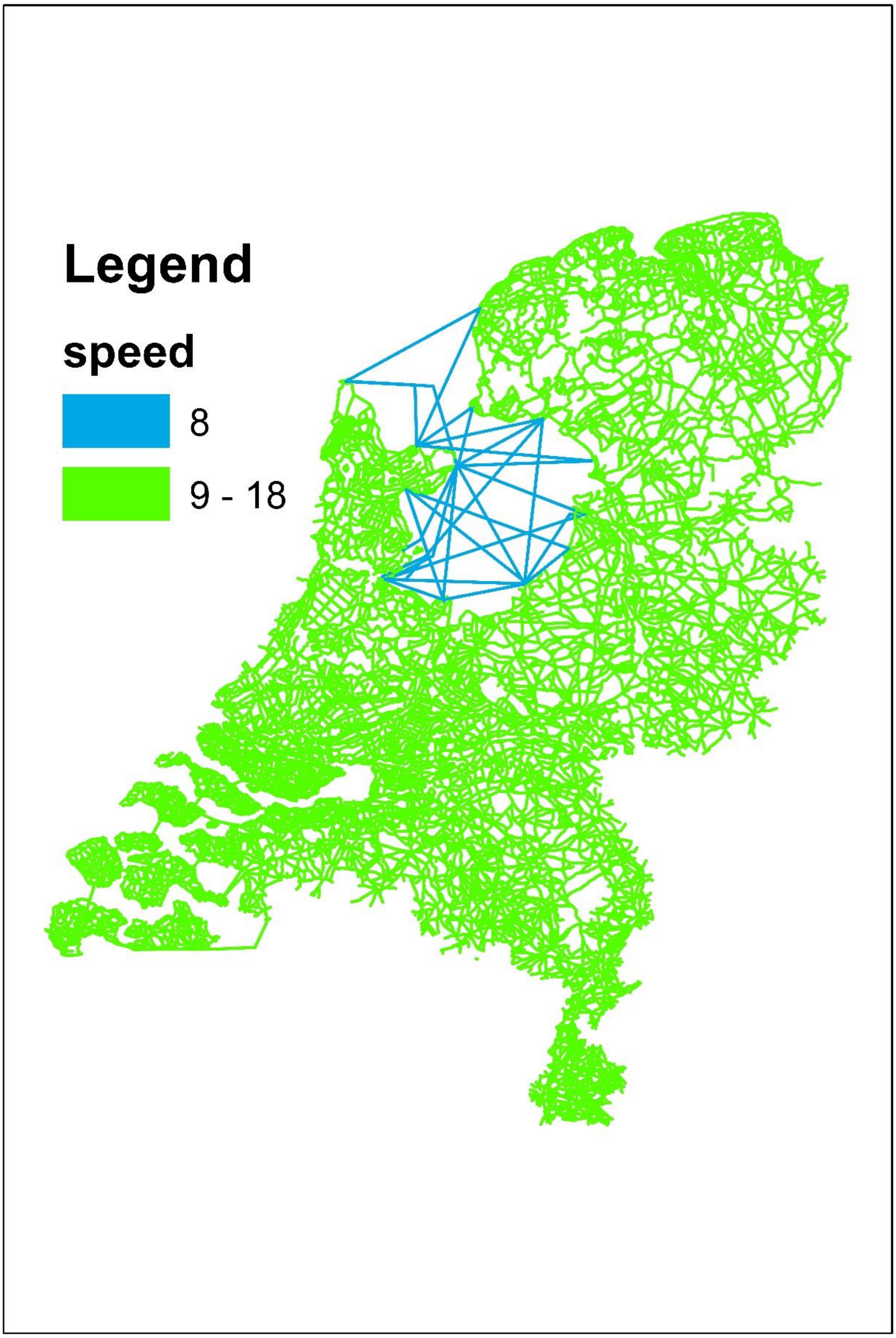


Map 3.7 approximate road usage 2001 based on betweenness

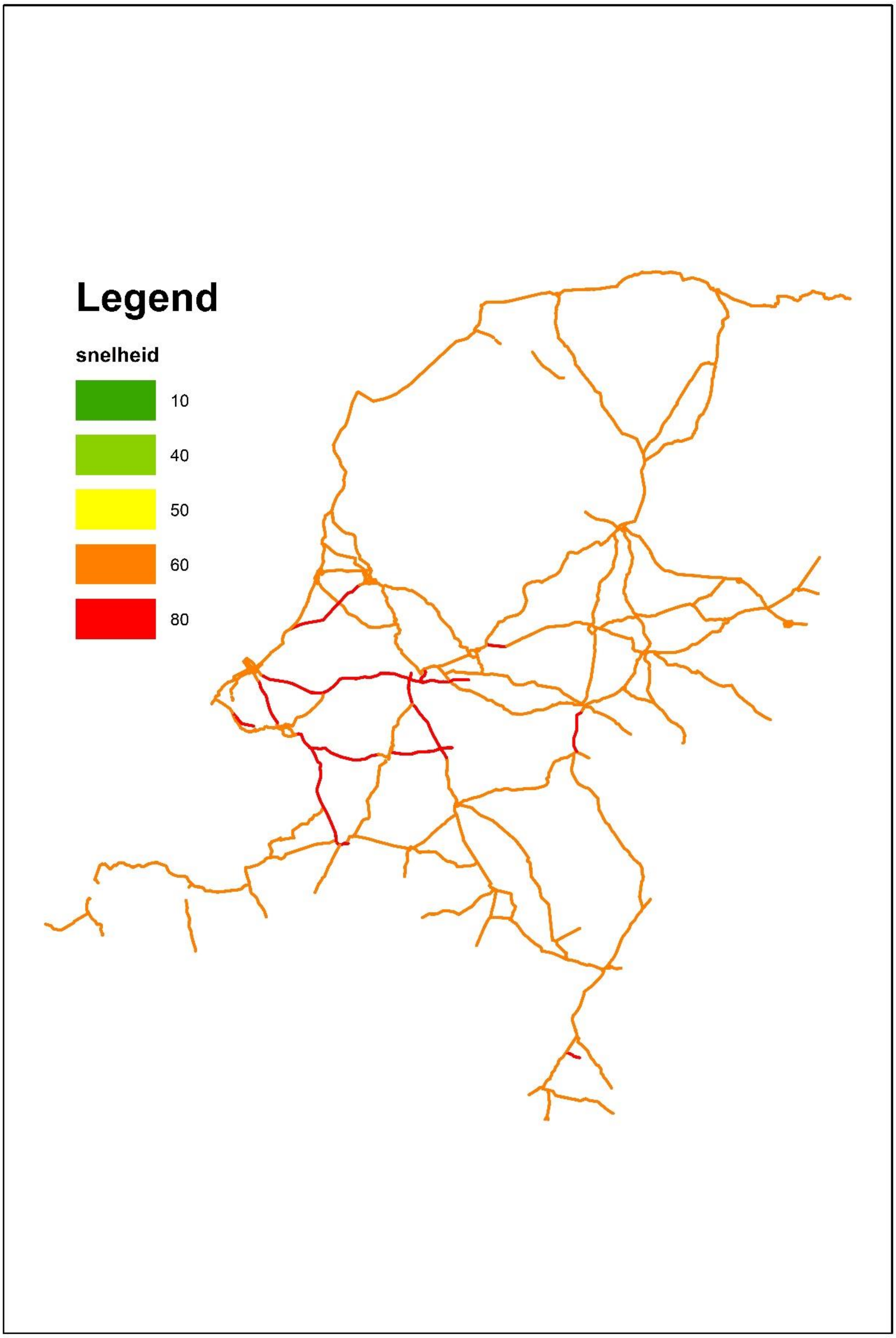


Map 3.8 approximate road usage 2007 based on betweenness

Map 4.1 Travel speeds 1848



Map 4.2 Highest travel speeds 1948



Map 4.3 Highest travel speeds 2007