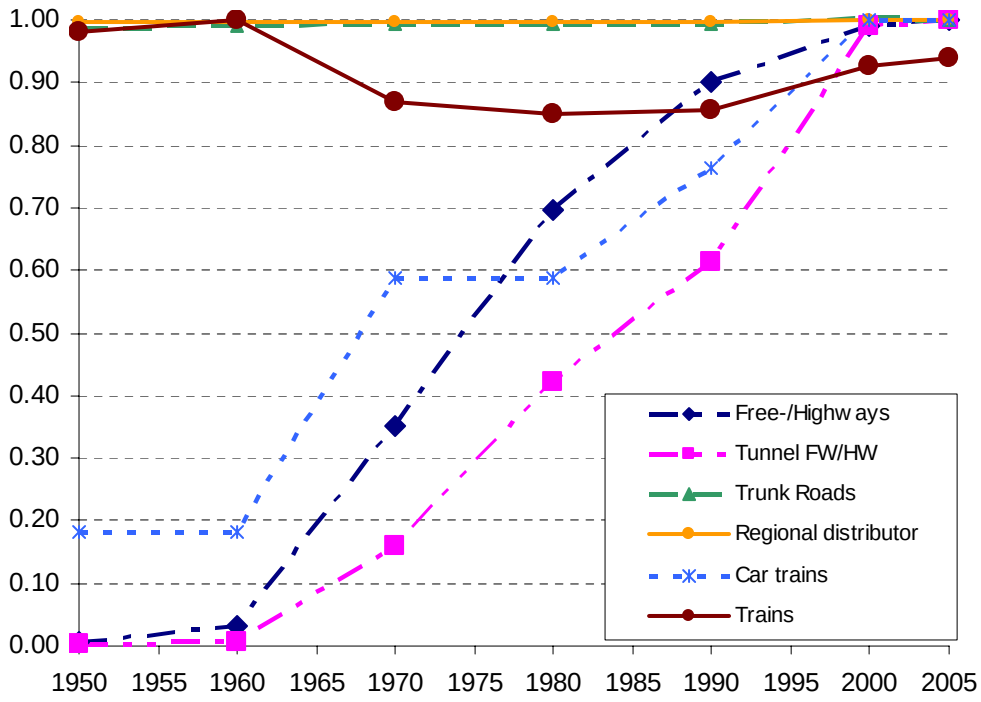

Graph-theoretical analysis of the Swiss road and railway networks over time

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Abstract

Recent research of complex networks has significantly contributed to the understanding how networks can be classified according to its topological characteristics. However, transport networks attracted less attention although their importance to economy and daily life. In this work the development of the Swiss road and railway network during the years 1950-2000 is investigated. The main difference between many of the recently studied complex networks and transport networks is the spatial structure. Therefore, some of the well-established complex network measures may not be applied directly to characterise transport networks but need to be adapted to fulfil the requirements of spatial networks. Additionally, new approaches to cover basic network characteristics such as local clustering are applied. The focus of the interest hereby is always not only to classify the transport network but also to provide the basis for further applications such as vulnerability analysis or network development.

Keywords

Transport Network Topology, Network Efficiency, Highway Network Development, Kernel Density

1. Introduction

The interest in the spatial structure of transport networks has been driven by the inherent impact of the network structure on its performance and its affects on land use. Early studies begun as early as 1960 but were limited by the data availability and the limited computational power. The focus of research was mainly on simple topological and geometric properties (Garrison, 1960; Garrison and Marble, 1962; Kansky, 1963; Harggett and Chlorey 1969). Later, with the availability of travel demand models researchers tried to explore how various network structures might influence traffic flow and travel pattern (Newell, 1980; Vaughan, 1987). More recently empirical studies analysed both quantitatively and qualitatively patterns of roads especially in urban areas (Marshal, 2005). However, recent network research emerged also from fields which are not directly linked to transportation. The modelling of complex systems as network of linked elements has become subject of intense study in the last years. A focus of research was the topology of modern infrastructure and communication networks such as the World-wide Web (Albert *et al*., 1999), the Internet (Faloutsos *et al*., 1999) or the Italian power grid (Crucitti *et al.*, 2004). Additionally, also networks like collaborating movie actors (Watts and Strogatz, 1998) or the academic co-authorship (Barabási *et al.* 2002) were investigated. Moreover, biological networks were analysed at different scales: Jeong *et al.* (2000) studied the metabolism of 43 organisms at the cellular level. Neuronal networks were evaluated by Watts and Strogatz (1998) and on a more aggregate level, Camacho *et al*. (2000) documented seven food webs.

Networks can be roughly classified into three groups (Albert and Barabasi, 2002): Regular Networks, random networks and systems of complex topology including small-world and scale-free networks. Commonly used regular networks have common basic cycles such as square or cubic lattices. The study of random networks has been motivated by the observation that real networks often appeared to be random. In the first arcticle on random graphs Erdõs and Rényi (1959) define a random graph as N labelled nodes connected by n edges, which are chosen randomly from the N(N-1)/2 possible edges. They defined important properties of networks: the distribution of node degree, which is the number of edges every node is connected to; in a random network it follows for example a binominal distribution. They further described the probability of the presence of subgraphs and defined the commonly used clustering coefficient which indicates the probability that two node neighbours are connected as well as the average path length. Furthermore they discovered that during the evolution of a network in terms of a growing connection probability, important properties such as clustering change quite suddenly.

Complex networks have a topology between those of random and regular networks and were introduced later. As an outstanding example Watts and Strogatz (1998) described the

construction and the properties of small-world networks: By rewiring or adding links randomly to regular graph shortcuts between formerly distant nodes are created which leads to a substantial drop in the average path length, which is proportional to the number of new shortcuts. The degree distribution still follows a Poisson distribution even though with a smaller λ–coefficient while the clustering coefficient stays high.

Several of the empirical results discussed above (Albert *et al*., 1999, Barabási *et al.,* 2002) demonstrated that many large networks are scale free which means that their degree distribution follows a power law. Barabási and Albert (1999) explained this specific property by describing the growth of such networks: Starting with only a small number of nodes any additional node is attached to the existing ones with a probability which depends on the degree of the existing node.

Although the presence of transportation infrastructure as network of daily life, only little literature on transportation network analysis can be found. A basic difference to other, rather virtual networks is that transportation networks are embedded in real space where nodes and edges occupy precise positions in the three dimensional Euclidian space and edges are real physical connections. Therefore spatial networks are strongly constrained which has consequences for the degree distribution and the number of long range connections. In planar networks most crossing of two edges leads to a new node. Additionally, it is important to reflect that the addition of links is costly which avoids regular networks becoming scale-free (Barabási, 2003).

1.1 Attempts at graph theoretical analysis of transportation networks

Xie and Levinson (2007) highlight the link-centric nature of road networks. Because recent network topology research deals broadly with node-centric, non-weighted networks those concepts fail to consider links properly as the active parts of transportation networks. In transportation networks the hierarchy is given by the functional characteristics of the links. The functional classification reaches from local streets with access to the land uses over trunk roads to arterial roads and to freeways. Based on the different link types and their service levels they calculated the entropy measure according to Shannon (1948) for idealised networks. Additionally, they defined four typical connection patterns: Starting with the definition of circuits where at least two paths between any pair of nodes, which share not one common link, they define a measure called ringness which is the quotient of the length of arterials on rings and the total length. Equally defined is the measure for the webness. The sum of ring- and webness equals the circuitness which in turn defines the treeness as the percentage of the arterial network that not belongs either to a ring or a web.

These measures are calculated here for the upper levels of the Swiss network. The changes over time are traced by the measures for the years 1960 to 2000 in ten year steps as well as for the present state (2005) and the forecast network state in 2020.

A further attempt to describe transportation networks was undertaken by Claramunt and Jiang (2004) turning streets into nodes and intersections into edges, what has been named 'dual graph'. The intersection continuity rules were using the street name information. Porta *et al.* (2006) found such a continuity rule unsatisfying because of the lack or only incompleteness of such information in many network databases. Therefore they introduced an intersection continuity model which uses principles of 'good continuation', based on the preference to go straight ahead at intersections and using basic geometrical information of junctions to detect continuing roads. A further approach to cover continuity might be Hillier's space syntax (Hillier and Hanson, 1984) but it was not yet used for network analyses. Claramunt and Jiang demonstrated the presence of small-world characteristics using such a dual approach for large street networks, which means that every node is only a few steps away from other nodes, but without scale-free behaviour of the degree distribution. Porta *et al.* analysed six quadratic 1 square mile cut-outs from six topologically different towns by the dual approach and found power law behaviour for the degree distribution. However, because of main streets (with a high dual graph node degree) are more likely to connect with secondary (or low connected) streets than to streets of the same hierarchical level, significant differences to non-spatial scale free networks were found. Moreover, it became apparent in their work that the cut-outs differ substantially between each other in terms of number of nodes and edges and they were simply too small to deliver enough cases for a structural distribution analysis. This leads to the main issue of analysing networks by the dual graph approach. All spatial information is lost during the transformation from edges to nodes and vice versa. Therefore Crucitti *et al.* (2006) started to investigate the primal graphs of urban street networks not only by the common measures of degree distribution or average path length but also by centrality measures which became a fundamental concept in network analysis since its introduction in structural sociology. They detected that transportation networks have to be analysed as weighted networks, whereas the weights are the length of the edges. However they did not approach the transportation network as multiple weighted network: For the transportation engineers capacity, travel demand and speed/travel time are as important as the length of a link. Therefore the weighting in this paper is twofold, covering links and nodes: The link weight may be considered by travel time, link load or capacity. Analogous measures are also possible for nodes which represent junctions. The presence of zones which are linked to the network extends the weighting possibilities. The zones may be seen as relevant nodes for the analysis. The relations between zones may be weighted for example according to population or GDP. To make a connection between demand and the rest of network, zones are linked to several nodes in their proximity.

This work extends the recent measures of centrality to cover the multi-criteria-weighted characteristics of transportation networks and incorporates analyses both at link and zonal level. Moreover, it compares networks not horizontally but longitudinally by comparing the network characteristics from 1950 to 2000 in ten year steps and discusses the relevance of these measures on transportation issues.

2. Centrality measures and their application to transportation networks

2.1 Degree and closeness centrality

Degree centrality is based on the idea that important nodes have the largest number of adjacent nodes. The normalised degree centrality C_D of the node i was defined by Freeman (1977 and 1979):

$$C_i^D = \frac{k_i}{N-1} = \frac{\sum_{j \in N} a_{ij}}{N-1} \quad (1)$$

where k_i is the number of links a_{ij} that connects node i to other nodes and N is the total number of nodes in the network.

For land based transportation networks (but not for those of air transport) degree centrality is limited due to spatial constraints, at least as long as nodes that stand for junctions. However, for nodes that stand for zones degree centrality can be interpreted as the aggregate demand of a given zone.

Closeness centrality measures the inverse of the average shortest path distance from node *i* to all other nodes in a given network and was introduced by Sabidussi (1966).

$$C_C = \frac{N-1}{\sum_{j \in N; i \neq j} d_{ij}} \quad (2)$$

Besides the network structure closeness centrality is highly dependent on the geographical position of node i in the normally finite network. Therefore nodes in spatial networks near to the geometrical centroid of a network are much more likely to have high C_C measures. The concept of closeness centrality is directly depending on the size of the network which makes it impossible to compare networks of different scale.

If closeness centrality is based on travel times rather than distance and zones are treated as nodes the weighted closeness centrality has the following form:

$$C_i^C = \sum_{j \in N, i \neq j} \frac{\sum_{i,j \in N, i \neq j} W_j TT_{ij}}{\sum_{j \in N, i \neq j} W_j} \quad (3)$$

where Wj is the weight of demand zone j and TTij the travel time between the nodes i and j. Whereas closeness centrality weights all relations equally independent of the distance,

accessibility (Rietveld and Bruinsma, 1998 and Geurs, and Ritsema van Eck, 2001) weights attractiveness of the nodes with the necessary travel time to these points by means of a negative exponential function, which is more realistic for transportation applications as observed travel demand shows the same patterns. An extensive analysis of the development of accessibility in Switzerland between 1950 and 2000 is already available (Axhausen *et al*. 2006, Tschopp *et al*. (2005) and Fröhlich and Axhausen (2005)). Therefore, the closeness centrality is not pursued here.

2.2 Betweenness centrality

The betweenness centrality of a node i is defined as the number of the shorthest paths between all other nodes which pass through i (Freeman, 1977).

$$C_i^B = \frac{1}{(N-1)(N-2)} \sum_{j,k \in N; j \neq k; j; k \neq i} \frac{n_{jk}(i)}{n_{jk}} \tag{4}$$

C_i^B is normalised and reaches the highest value of 1 when every shortest path involves node i. An analogously defined betweenness for links can easily be derived. As the relevant paths are those between zones, the result of traffic assignment models deliver inherently the betweenness measure, at least when an all-or-nothing assignment is used. However, more sophisticated and well-established assignment models using the principles of equilibrium (Wardrop, 1952) that reflect the capacity of nodes and links as well lead to solutions which are more realistic. To assess the road network as a double weighted network, a demand matrix would be required, but is not available for the years 1950 to 1990. For this reason, a so defined transportation-aware equivalent for betweenness centrality is only available for the year 2000.

2.3 Efficency and straightness centrality

2.3.1 Global Efficieny

Originated by the idea that the efficiency of spatial networks distributing information might be measured by comparing the length of the shortest paths between (Latora and Marchiori, 2001) nodes with the crow-fly distance, Boston's (Latora and Marchiori, 2002), Barcelona's and Madrid's (Vragovic et al., 2004) public transport systems were analysed on efficiency centrality (C_i^E) or straightness centrality (C_i^S) respectively and revealed remarkably high values.

$$C_i^S = \frac{1}{N-1} \sum_{j \in N; j \neq i} \frac{d_{ij}^{\text{crowfly}}}{d_{ij}} \tag{5}$$

$$C_i^E = \frac{\sum_{j \in N; j \neq i} \frac{1}{d_{ij}}}{\sum_{j \in N; j \neq i} \frac{1}{d_{ij}^{\text{crowfly}}}} \tag{6}$$

As in public transport networks each node acts normally also as demand origin node every connection has some relevance. However, the present studies did not incorporate the importance of different connections for example by weighting with travel demand (C_i^W). Such an extended attempt might be even more essential if large road networks (Porta *et al.,* 2006) are analysed whose demand relations show usually a wide range of values including relations with zero demand. Therefore, the global efficiency is evaluated according to equation 6.

$$C_i^{ws} = \frac{\sum_{j \in N; j \neq i} W_j \frac{TT_{ij}^{crowfly}}{TT_{ij}}}{\sum_{j \in N, i \neq j} W_j} \tag{7}$$

The above weighted straightness measure C_i^{ws} captures how much the paths starting from a given node i deviate from crow fly paths, weighted depending to the importance of the node j. By using travel times from traffic assignment models instead of distances congestion and specific route choice behaviour can be incorporated as well which lead to a more appropriate measure.

2.3.2 Local efficiency

While the above measure of straightness centrality assesses a network on its ability to spread information globally, measures of local efficiency were introduced as counterpart of the clustering coefficient. The clustering coefficient of a given node indicates the probability that direct neighbours of a given node are directly connected as well. Besides the local efficiency the clustering coefficient is therefore often related to the ability of a network to respond on link failures. According to the definition of Latora *et al*. (2001), the local efficiency measures the path distances between neighbours of a given node passing only through other elements than i in the subgraph of direct neighbours of i. As the analyses of this work are based on zones rather than actual junctions none of the proposed formulations is directly applicable, as one zone is generally connected to several junctions. Therefore an alternative measure to account for the local efficiency is introduced which reflects the 2-dimensional character of the zone: the cumulative road length of all roads within a circle with the population weighted

centroid of the zone as center and a radius of 5km reflects the ability of the local network to respond to link failures. Other radii where also tested, but the results with 5km revealed the real density characteristics best. An alternative measure reflects the product of length and capacity instead of length only.

To resolve the problem of spatial discontinuity of such a location specific measures the use of interpolation techniques is advisable. The kernel density estimation is an interpolation technique that is appropriate for point data, which provides density estimates for all parts of a region by fitting a smoothly curved surface. Various kernel functions have been applied to similar problems, including the normal distribution function (Kelsall and Diggle, 1995), the quartic function (Bailey and Gatrell, 1995) and the triangular function (Burt and Barbar, 1996; Leitner and Staufer-Steinnocher, 2001). However, the choice of the kernel function is less critical than that of the chosen search radius from each point, called bandwidth (Thurstein-Goodwin and Unwin, 2000). For the presented work, the quadratic kernel function as described by Silverman (1986, 76) and implemented in ArcGIS 9.2 is used here:

$$\hat{f}(x) = \frac{1}{nh^2} \sum_{i=1}^{n} \kappa\left\{\frac{1}{h}(x - X_i)\right\} \tag{8}$$

with

$$\kappa(x) = \begin{cases} 3\pi^{-1}(1 - x^T x)^2 & \text{if } x^T x < 1 \\ 0 & \text{otherwise} \end{cases} \tag{9}$$

where x_1, x_2, ….., x_n are the points within the region $\boldsymbol{R}$, $\boldsymbol{h}$ is the bandwidth and κ(.) is the spatial probability density function. In this work, the total length and the total length times capacity have been assigned to the centroid of each traffic zone and a bandwidth of 5000 meters have been applied while the individual cell size of the resulting surface has been ascertained to 100 m times 100 m.

3. The transportation network development in Switzerland 1950-2000

3.1 Data

The network data for the years 2000 and before was taken from a previous project at the Institute for Transport Planning and Systems of the ETH Zurich, ViaStoria (Berne) and the Insitute d'Histoire (Univeristy of Neuchâtel) which created road and rail network models and matching socio-economic databases covering each of the currently 2896 municipalities and the period since 1850 with steps at 1888, 1910, 1930, 1950 and then every ten years until 2000 (Fröhlich and Axhausen, 2005 and Fröhlich, Frey, Reubi and Schiedt, 2004). The data for 2005 and 2020 are based on the freeway construction plans of the Swiss Federal Roads Office and cover only freeways.

All important changes of the main roads and free-/ motorways such as opening, improvement or the construction of additional lanes were traced and documented in the database. The links are described by their direction, length, free speed, capacity and the parameters of the capacity restraint function, which links the link load to speed. As some of these parameters depend on the respective vehicle fleet, changes in driver behaviour, differing speed regulations and changed road qualities, the capacity and its restraint function had to be adapted for every network state. As no demand matrices describing the traffic flows between the zones over the years were available for a detailed calculation of the speeds and the travel times between the zones, it was necessary to make assumptions about the mean speeds by link type. The used network model employs 35 different road types which allows a reasonable differentiation.

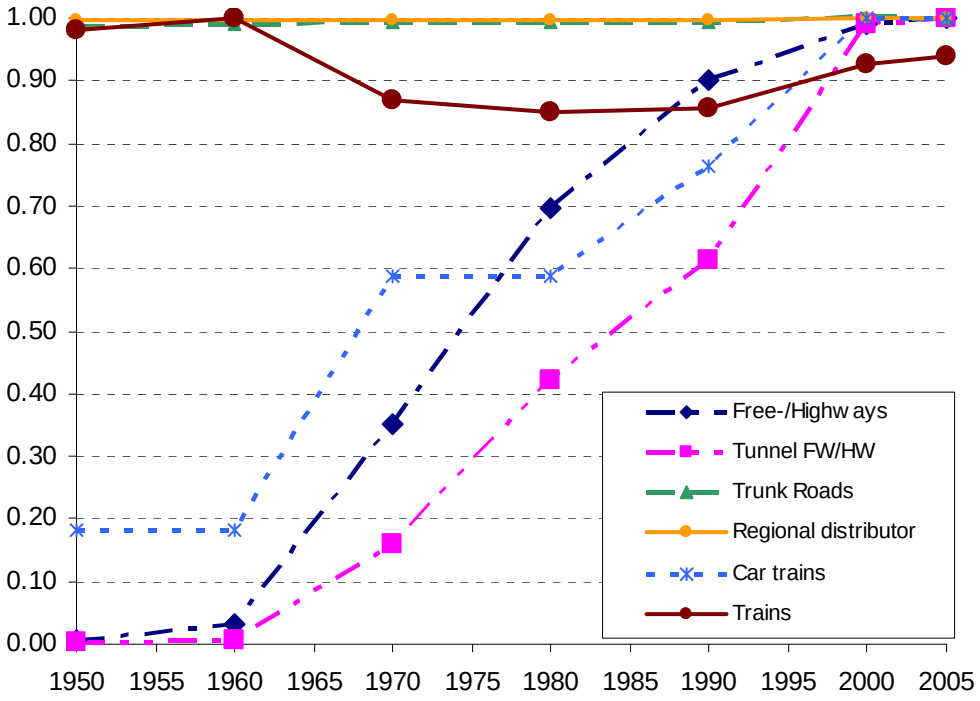
The assumptions about the mean speeds were based on a substantial review by Erath and Fröhlich (2003) including evidence from Swiss and German and US sources, where the ongoing development of the HCM (Highway Capacity Manual) since the 1940s has generated copious data. The review integrated information about measured speeds, capacity estimates and traffic counts to arrive at consistent sets of free flow speeds, capacity restraint functions, capacities estimates and mean speeds by link type and decade (1950 to 2000). With these sets (free flow speed, capacity and capacity restraint function) and the observed traffic counts at about 350 traffic counting stations, the speed distributions by link type and decade were calculated.

The population data, which is used only for the weighting, was taken from the censuses of 1950, 1960, 1970, 1980 and 1990. In the case of 2000, population data of the Bundesamt für Statistik from the beginning of 1999 is employed.

3.2 Aggregate Measures

Before describing the development of the transport network in Switzerland in detail, it is worthwhile to look at aggregate changes. There is a consensus in literature that macroscopically, the growth of infrastructure follows a logistic curve and that road infrastructure is also reaching saturation levels in developed countries (Grübler, 1990, Levinson, 2005). Figure 1 shows the development of the Swiss transportation network length by link type and is normalised for the year with the longest network length.

Figure 1 Normalised length of the Swiss Transport Network 1950-2005[1]



It is obvious that saturation was already reached for the trunk roads and local distributors in 1950. Planned as a new network within the existing one the free- and highway network shows the characteristic s-curve shape. Interestingly, the curve for tunnels underlies a time shift of around 10 years compared to the rest of the high hierarchy network. The length of the car train links is substantially smaller (2005: 92km) than the free-/highway (2000: 4063km) or

[1] Effective length 2005: Free-/Highways: 1930km; Tunnel FW/HW: 176; Trunk roads: 6195km; Regional distributors:14827km; Car trains: 92km, Trains: 5069km

even the trunk-/regional roads (2000: 42043km). Nevertheless, the growth shows similar patterns as the other evolving network parts.

The rail network was decreasing between the years 1960 and 1980 because some minor lines had to close for economical reasons, like the Maggia valley rail. These railway lines were mostly replaced by bus services. Since 1990 with two major projects called 'Bahn 2000' and 'NEAT' the rail network is increasing again. However, as the objective of this paper is the development of transport infrastructure networks, it might be reasonable to focus on the road network only as the rail network showed only minor extensions. However, considering the development of service density and speed an analysis of the rail network might be an interesting topic for further work.

3.3 Topological measures

Xie and Levinson (2007) stated that previous studies describing network topology have rarely investigated the patterns quantitatively and that the connection patterns of road networks therefore remain only poorly understood. Harggett and Chorley (1969) described however two basic structures for planar transportation networks: branching and circuit networks. A circuit is defined as a closed path with the same vertex as start and end. Branching network are characterised by tree structures with multiple connected links without any circuits. Gibbson (1985) introduced the cyclomatic number indicating the number of circuits in a network. Based on those, Xie and Levinson developed new measures incorporating also the length of the links: The ringness and webness indicates the proportion of the network length belonging to a circuit or a web respectively. The sum of both equals the circuitness, which itself is used to calculate the treeness.

$$\phi_{\text{Ring}} = \frac{\text{Total length of arterials on rings}}{\text{Total length of arterial}} \tag{10}$$

$$\phi_{\text{Web}} = \frac{\text{Total length of arterials on webs}}{\text{Total length of arterial}} \tag{11}$$

$$\phi_{\text{Circuit}} = \phi_{\text{Ring}} + \phi_{\text{Web}} \tag{12}$$

$$\phi_{\text{Tree}} = 1 - \phi_{\text{Circuit}} \tag{13}$$

Xie and Levinson have calculated these measures for idealised networks and proved their applicability and relevance in quantitatively describing road network structures. Therefore the measures are applied to capture the topological development of the high hierarchy network in Switzerland.

3.3.1 Network evolvement

The start of the upper hierarchy of the road network dates back to 1955 when the first freeway was completed, which was planned as a parkway to diminish the travel time between the city of Lucerne and its main recreational countryside and was paid by the Canton. After the construction of two other freeway sections on local initiatives in other Cantons and with the increasing motorisation it became obvious that a national policy on the network development had to be worked out. The 'Nationalstrassengesetz', the law on nationally funded motorways and other roads, described the financing, the network and its planned development. The sections along the principle axis between east and west as well as north and south were prioritised and should be opened in as contiguous parts wherever possible. The planning was assigned to the national government and the financing provided by increases of the fuel tax, raised by the federal government. Alongside, then present bottlenecks were to be considered and parts of the network which might improve such situations should also be prioritised. At that time there was also a consensus that the main part of the travel demand is generated by cities and therefore the new level of network should serve the cities directly. Hence, urban beltways were not considered in the planning process, which has strong implications for the proposed measures and shows their ability to cover main network characteristics. Instead of urban beltways so-called 'Express-Strassen' were planned to connect the freeway endings passing directly through the cities.

While the early network development process was mainly driven by economic considerations, ecologically motivated initiatives emerged in the 1970ies and lead to objections against the planned alignments and even against entire freeway sections. In one case, where the route design was controversial, a referendum was initiated by the opponents [2]. Only by proposing an alternative including two tunnels a majority could have been convinced not to vote against the freeway. Later, in the case of the freeway 4, connecting Zurich with Zug and Lucerne, the opponents were more successful and achieved a moratorium. Moreover, the planned 'Express-Strassen' in Zurich were abandoned after a referendum although some parts had already built. Interestingly, the relevant file with the first motorway network plan is stated as being lost at the National Archives (Fischer and Volk, 1999). Instead of the 'Express-Strassen' it was decided to expand the network around Zurich with two major by-passes in 1971. During the years it became also apparent that the proposed development program could not be maintained, mainly for two reasons: Firstly, it became obvious that the construction cost were substantially higher then the original prognoses (Gätzi, 2004), which lead to several increases of the fuel taxes. Therefore some parts of the network were delayed, like the freeway in the

[2] Interested parties can get any issue on the ballot by collecting the required number of voter signatures.

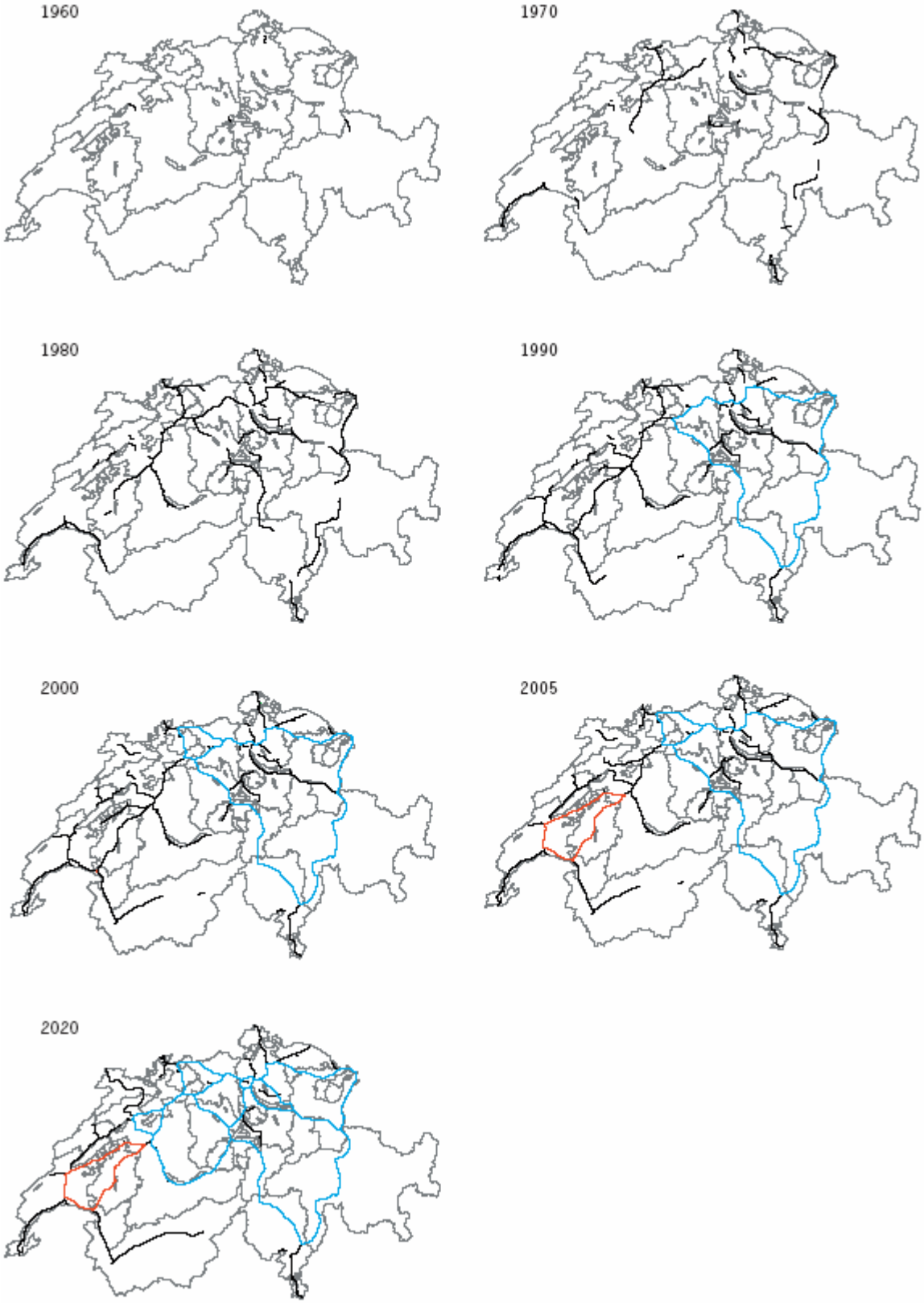
main valley of the Canton Valais. Additionally, several objections slowed down the process. On the other side, the secession of the Canton Jura from Bern lead to the addition of the 'Transjuranne', a freeway serving only the economically weakest Canton of Switzerland.

All these points make it quite clear that the expansion of a upper level road network is strongly affected by the political circumstances and therefore very difficult to forecast. However, the measures proposed by Xie and Levinson are able to cover the outcomes of delays and suspensions, as these have a direct influence on the number of subgraphs as well as the ring- and webness. Figure 2 shows the freeway network states for the years 1960, 1970,1980, 1990, 2000, 2005 and the prognosis for the year 2020.

Following the policy of having the major centres connected first, the earliest routes are those between Geneva and Lausanne in the western parts and Basel, Bern, Zürich as well as St. Gallen in the north. As in Figure 1 indicated the routes through the Alps which involved major tunnels (and bridges) were constructed later. Until 1980 no circuit was present, although back then already 65% of the final network was built. As recently as 1985 the first circuit with the two major alpine tunnels Gotthard and San Bernardino was closed. With the construction of the direct link between the two largest Swiss cities in 1996, again involving a tunnel, a second circuit was established. A national exposition in 2002 boosted the project of an additional freeway route linking the capital Bern via Yverdon to Lausanne passing mainly through sparsely populated areas which was commissioned in 2001.

Zurich will get a full freeway bypass in 2010 when the western extension will be finished. Although, if the first city beltway will be put in operation in 2020 is not clear yet as the necessary lake tunnel is in the long term planning documents only mentioned as alternative for another project. Furthermore, the tunnel is politically rather disputed and concrete planning has not started yet. In contrast, the construction of the city tunnel in Biel has begun in 2006. However the resulting additional circuit is not a city beltway but the result of linking two further freeways.

Figure 2 Development of the Swiss freeway network 1960-2020
(black: part of a tree; blue part of ring 1; red: part of ring2)



While the aggregated network growth slowed down since 1990 the absolute and relative tunnel growth is unaffected. Ultimatly, more than 50% of the projected links in the time frame between 2005 and 2020 are tunnels for two main reasons: First, most of the projected routes lie in urban areas where space is scarce. Along this, environmental issues have gained more and more importance for demanding urbanistically acceptable solutions with low noise emissions. Second, the other main part of the projected routes is mainly connecting mountainous regions where tunnels are sometimes the only solution to deal with the topography.

Table 1 Structural measures for the Swiss freeway network 1960-2020

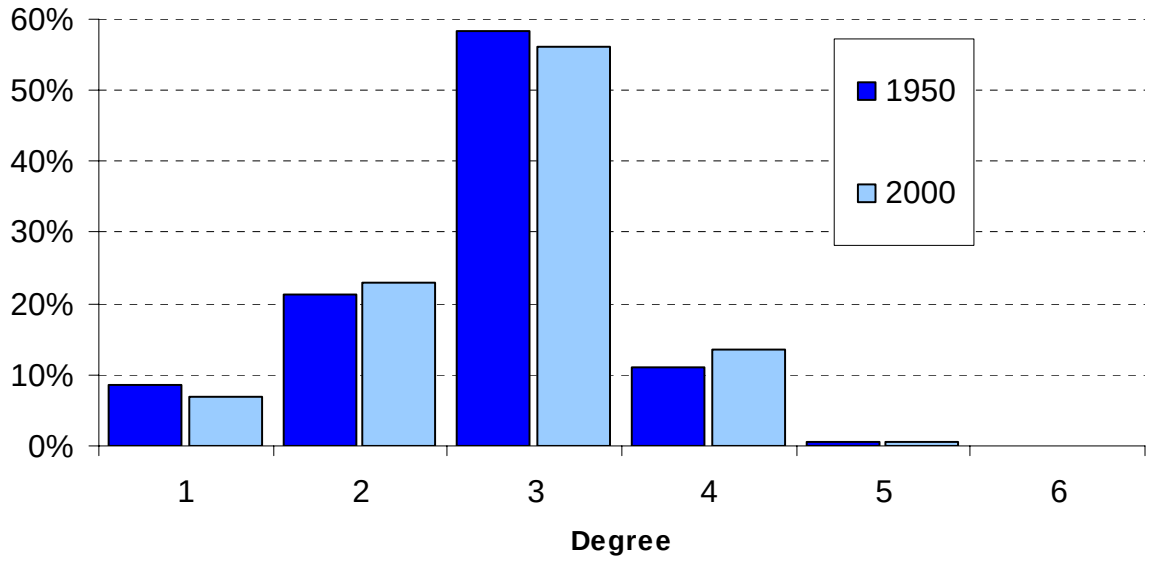
Year	Length [km]	Percentage Tunnel	Percentage Tunnel new roads	Subgraphs	Share of the longest subgraph	Circuitness	Treeness
1960	62.50	1.75	1.75	4	0.34	0	1
1970	678.23	4.14	4.39	26	0.26	0	1
1980	1363.96	5.46	6.76	26	0.28	0	1
1990	1781.62	6.08	8.11	16	0.90	0.36	0.64
2000	2014.47	8.65	28.33	13	0.90	0.37	0.63
2005	2105.99	8.67	2.09	10	0.92	0.47	0.53
2020	2257.32	11.72	54.91	8	0.98	0.58	0.42

3.4 Centrality measures

3.4.1 Degree centrality

Degree centrality, defined as the number of links incident upon a node, is limited in land transport networks due to spatial constraints. Figure 3 shows the degree distribution of the Swiss national transport model in 1950 and 2000 and points out the constrained nature of the degree distribution in road networks which show therefore also high temporal stability. Nodes with degree 1 stand for dead end nodes, which typically appear at the end of a valley. Nodes with degree 2 represent either junction where minor roads, which are not covered in the National Transport Model, meet the higher hierarchy network or identify changes of the link type (e.g. changes of capacity/speed). The latter problem is even more distinctive if one would use highly disaggregate network data such as Teleatlas or NAVTEQ, as those networks use additional nodes to trace the course of curves. The majority of the nodes have degree three or four. Only a very limited number of nodes connects five and more links- Those nodes lay mostly in urbanised areas.

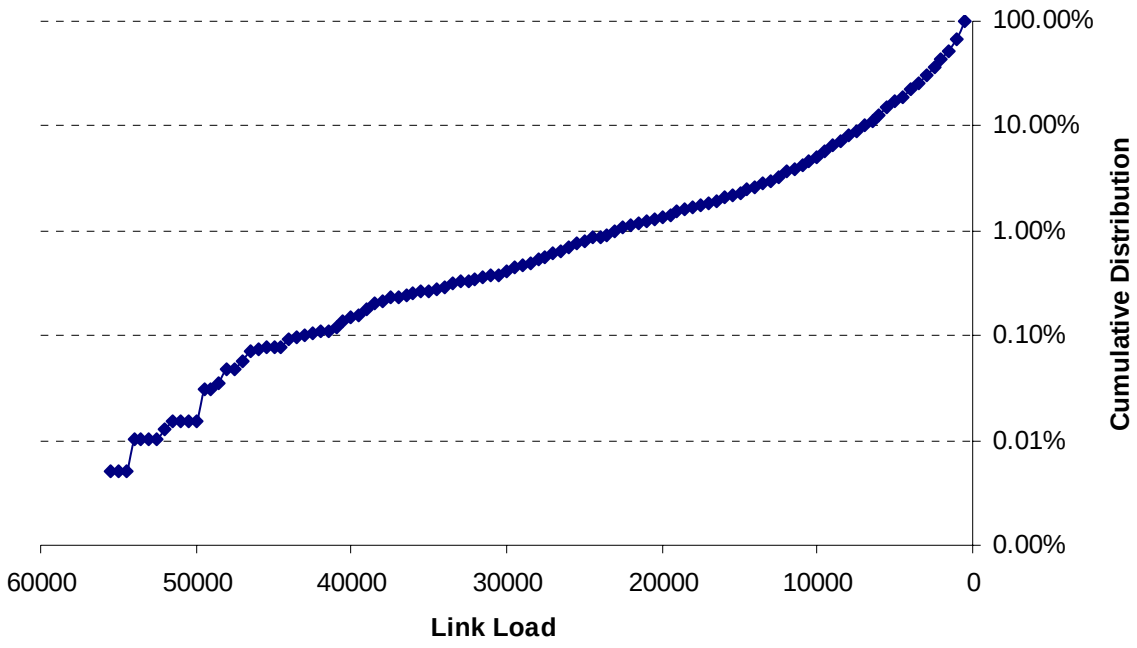
Figure 3 Degree Distribution: Network 1950/2000 (1950: N= 11'004; 2000: N=12'810)



3.4.2 Betweenness centrality

As described above, the direct application of betweenness centrality on transportation networks is the link or node load. The cumulative link load distribution (Figure 4) of the Swiss National model (Vrtic *et al.*, 2005) follows an exponential distribution. This is in line with the findings of Latora *et al.* (2006) for urban street networks of self-organised cities although their 'demand' resulted from analysing all paths between all nodes and neglecting different link speeds and link loads. This indicates that in both cases scale-free behaviour is present and might be an inherent propriety of self-organised road networks, as the main factors leading to the same distribution are different. In the first case, the hierarchy of the network with different link capacities and speeds induces more effective links which are in turn more favourable. In the latter case, the demand is ubiquitous and all links equally effective. Therefore, links in the centre of a given network are more likely to lie on a shortest path which might be one explanation for the scale-free distribution.

Figure 4 Cumulative distribution of link loads



3.4.3 Global Efficiency

The efficiency measures for every municipality are calculated according to Formula 6, using travel times instead of distances. This requires an assumption for the speed with which the crow-fly distances are divided in order to obtain crow-fly travel times. This speed was set to be 80km/h which would be the speed limit in a virtual tunnel connecting all municipalities with each other. In order to obtain one value for the entire network, a further step of weighing was employed:

$$E_{Net} = \frac{\sum_i C_i^{ws} \cdot P_i}{\sum_i P_i} \qquad (14)$$

Table 2 lists the results for the years 1950 to 2000 indicating also population data, the freeway network length in relation to the 2000 state and the standard deviation of the network efficiency measure on the municipality level. Although population and efficiency are not directly connected both grew constantly until 1980. During this period, the travel times decreased because of the technical advances of the automotives and the development of the freeway network. For the years 1980 to2000 the efficiency stayed almost constant, although the freeway network length was still growing. This has mainly two reasons: Further progress

in the automobile technology was not anymore transferable in higher travel speeds and the network was reaching its capacity limits resulting in higher travel times. Nevertheless, it might be questionable if the network was expanded in the wrong places. Having had augmented capacity where it was needed instead of connecting less densely populated region to the freeway network, further efficiency gains would have been possible. This finding might be qualified because capacity extension is usually connected with significant higher construction costs and is politically delicate. Moreover, one objective of the freeway network development was also unifying the country, which frequently turns out to be an important issue in the political decision process of Switzerland, due to its federal structure.

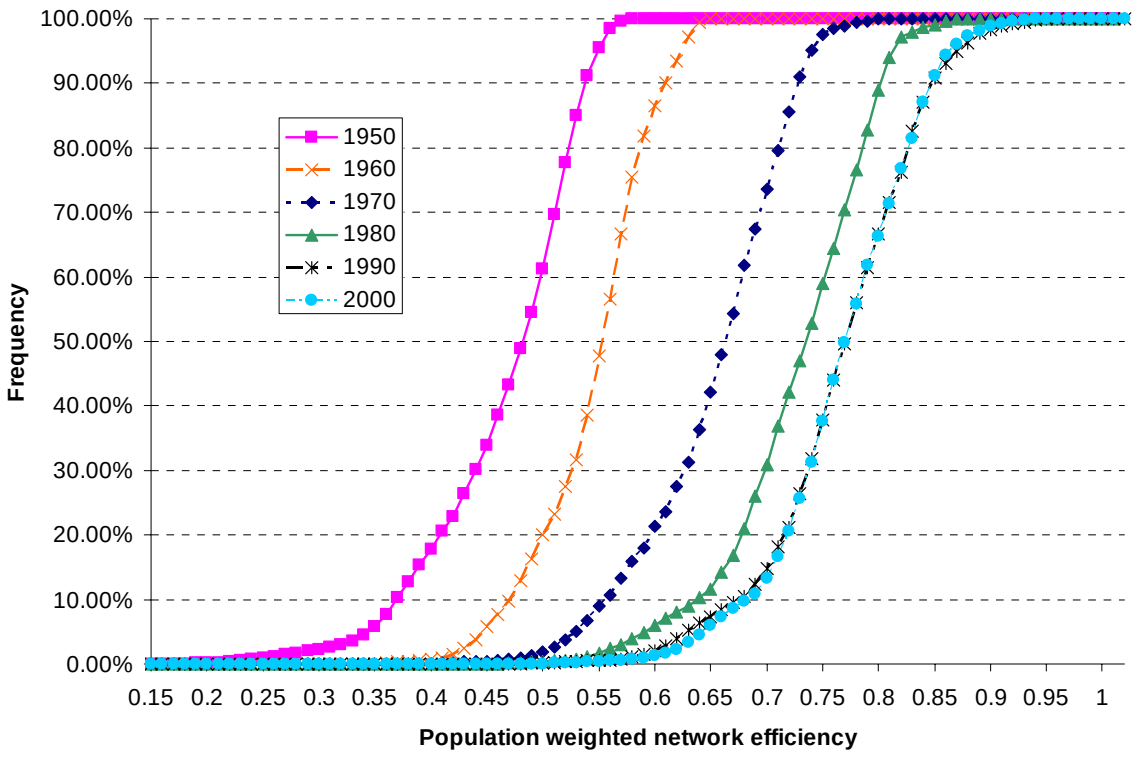
Table 2 Global Network Efficiency for the Swiss freeway network 1960-2020

Year	Population [Mio]	Freeway network length	Efficiency	Std. Deviation
1950	4.73	0%	0.45	0.068
1960	5.43	3%	0.54	0.052
1970	6.25	34%	0.65	0.066
1980	6.36	68%	0.74	0.067
1990	6.86	84%	0.77	0.071
2000	7.28	100%	0.77	0.066

As only few values are found in the literature, the comparison of the values is restricted to the findings of Latora *et al.* (2003). Including busses and subway, they report an efficiency of 0.72. Although the value is in the same range as for the Swiss road network, those two values are not comparable: Latora *et al.* calculated the network efficiency based on unweighted distances rather than travel times.

Figure 5 shows the cumulative distribution of network efficiency at the municipal level over the years 1950 to 2000. Except for the period between 1990 and 2000 the network efficiency grew continuously while the distribution pattern stayed stable. This means that with the construction of the freeway network the relative divergence between remote and central municipalities remained constant. The curves are best fit by a normal distribution indicating random network behaviour.

Figure 5 Cumulative distribution of network efficiency on municipal level 1950-2000



The spatial distribution of the network efficiency (Figure 6) measures exhibits on the one hand border effects but reveals also clearly effects of geographical centrality and freeway proximity on the other hand. Hence, municipalities near the border with freeway access have the highest values of network efficiency. This might be different if the study area would be widened and the neighbouring countries would be considered, too. But as the available data

for this area have a different scale and covers only major roads plus has more aggregated zoning, their inclusion would have biased the results by increasing the network efficiency globally: The highest values of efficiency can be found along the Freeway A1 from west to east connecting major agglomerations. The course of the A2, the second main freeway, is not as pronounced as the A1. The North-South traverse leads through less densely populated and more mountainous areas which both affects the population weighted efficiency measure. Municipalities without freeway access in proximity or being situated in less dense parts of Switzerland show typically low efficiency values. They are often located in mountainous areas where the paths from and to those places involve significant deviations from the crow-fly line.

Figure 6 Municipal network efficiency, 2000

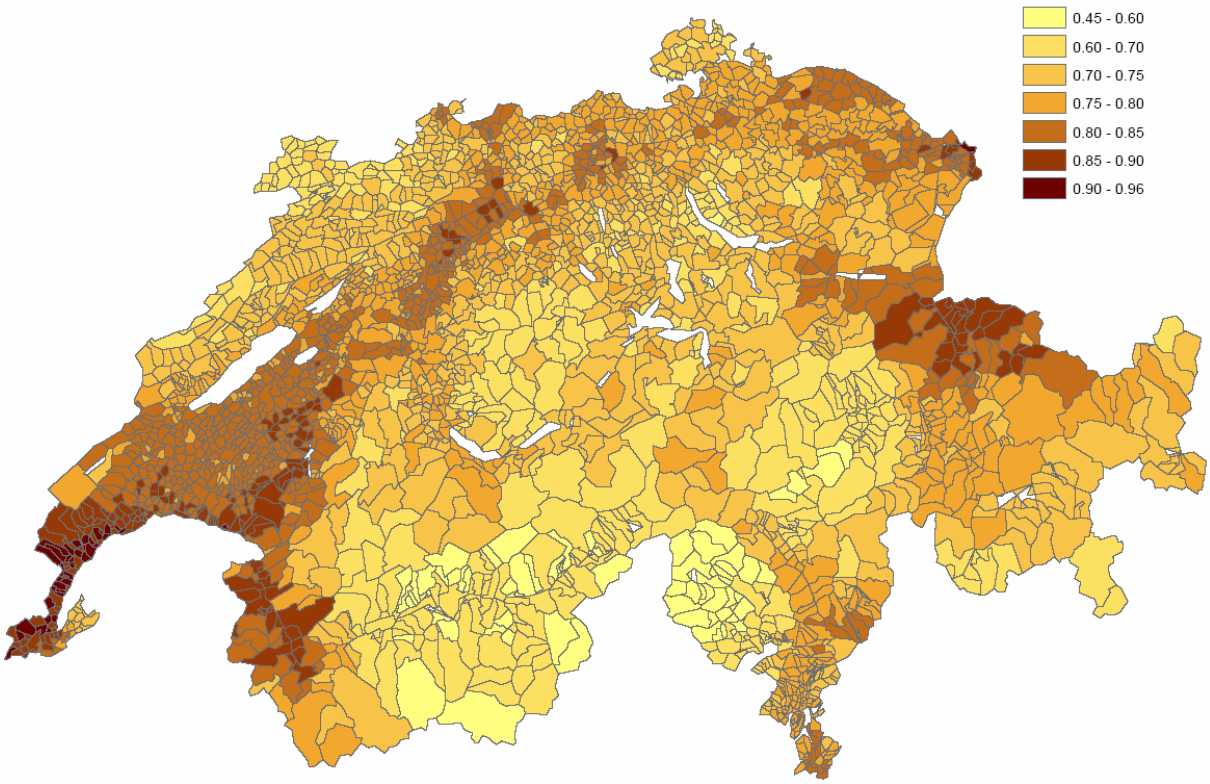
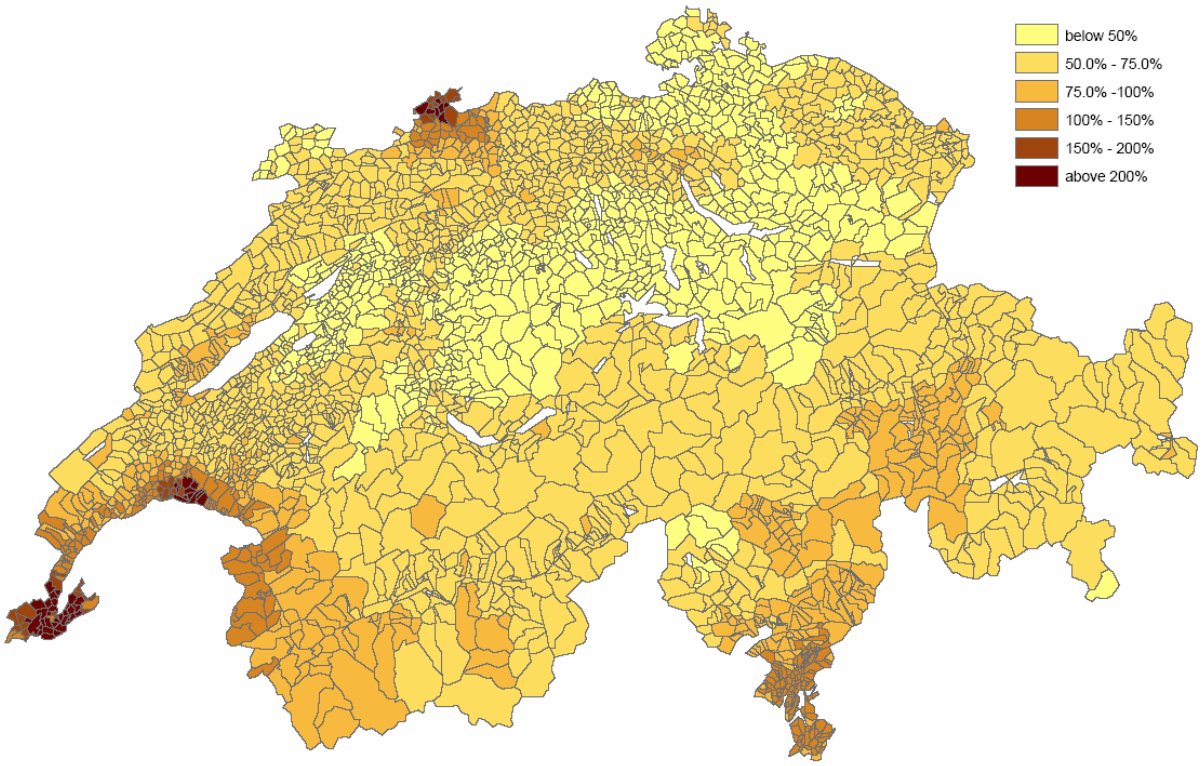


Figure 7 shows the growth of network efficiency from 1950 to 2000 and points out the distinctive development among the agglomerations of Geneva, Lausanne and Basle. Other major agglomerations with direct freeway connection like Zurich, Berne or Lucerne could not perform likewise, as their efficiency measure in 1950 was higher due to their more central location.

Figure 7 Growth of network efficiency 1950-2000



3.5 Local Efficiency

Road and Capacity Density

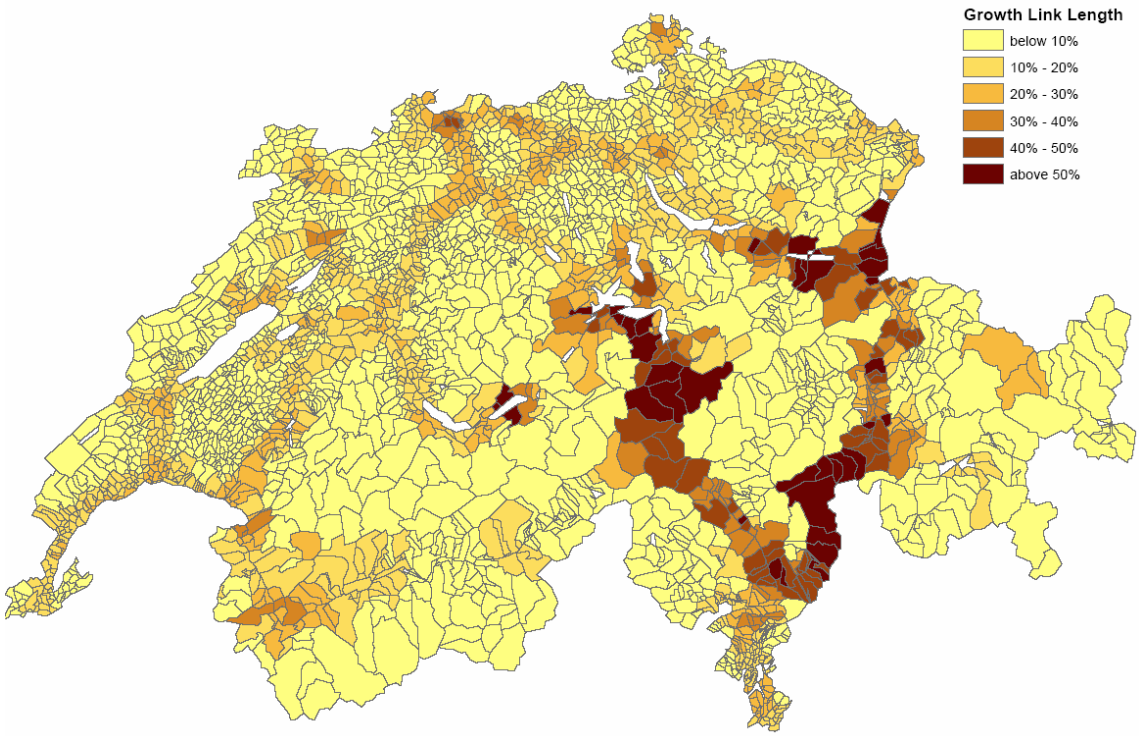
The local efficiency is assessed by the local network density, assuming that dense networks have a higher ability to respond on link failures smoothly and distribute demand more efficiently. According to Figure 1, it is expected that the road density only increase significantly along the newly constructed freeway corridors. In contrast to road density, an increase of the capacity seems appropriate even without newly constructed roads due to the altering of further factors which influence road capacity. Technological advances in car

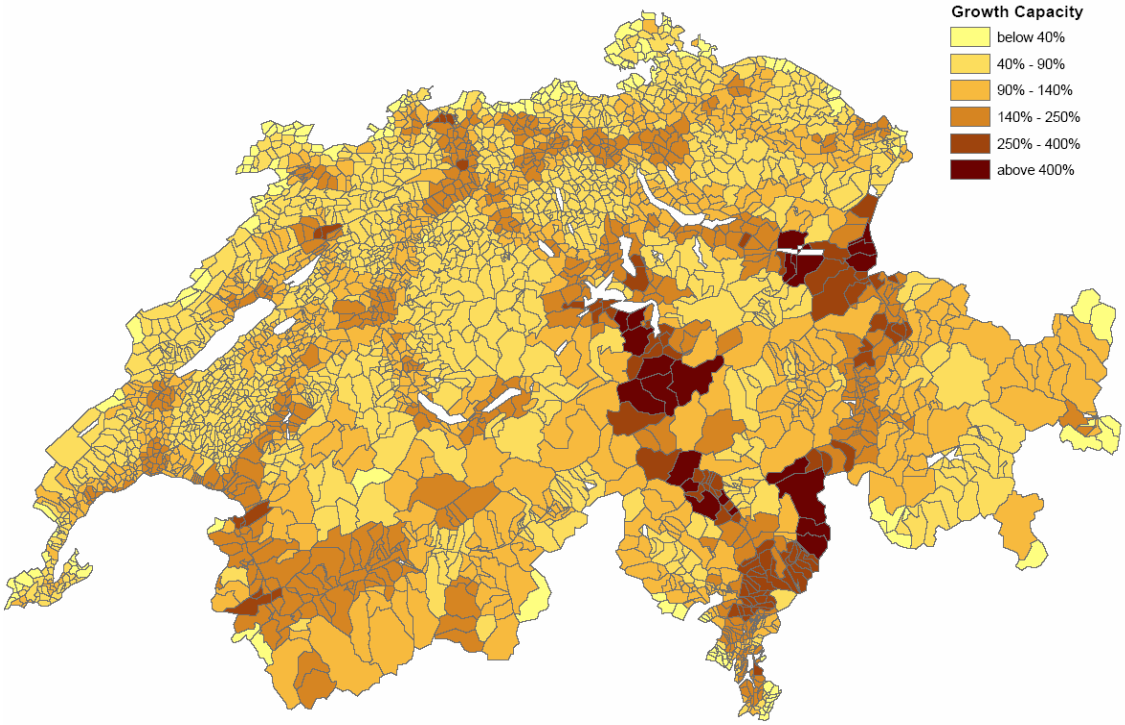
construction improved the power/weight ratio leading to a more homogenous vehicle fleet which resulted in a higher capacity even for unmodified links.

The road length density for every zone is calculated by summing up all links within a radius of 5 km from the population weighted centroid. Thus, links farther than 5km from the centroid are not contributing which is a desirable characteristic for a local efficiency measure. The capacity density is equal to the product of road length and its capacity.

Both figures show clearly the expected network growth along the freeways which is particularly obvious in more rural areas, as the road density started from a low level there. Beside these corridors, the development between road and capacity density is different: Whereas effects of technology advance, in-vehicle manufacturing raised the capacity globally, additional roads are restricted to the freeway corridors. The figure would look differently if local roads would have been included, as their net length increased with the suburbanisation. Because of the lack of a centralised road network data archive for Switzerland, an integrated approach will always be connected with an enormous amount of data collection work, but would be essential when analyses involving local roads were envisaged.

Figure 8 Growth of road length and capacity



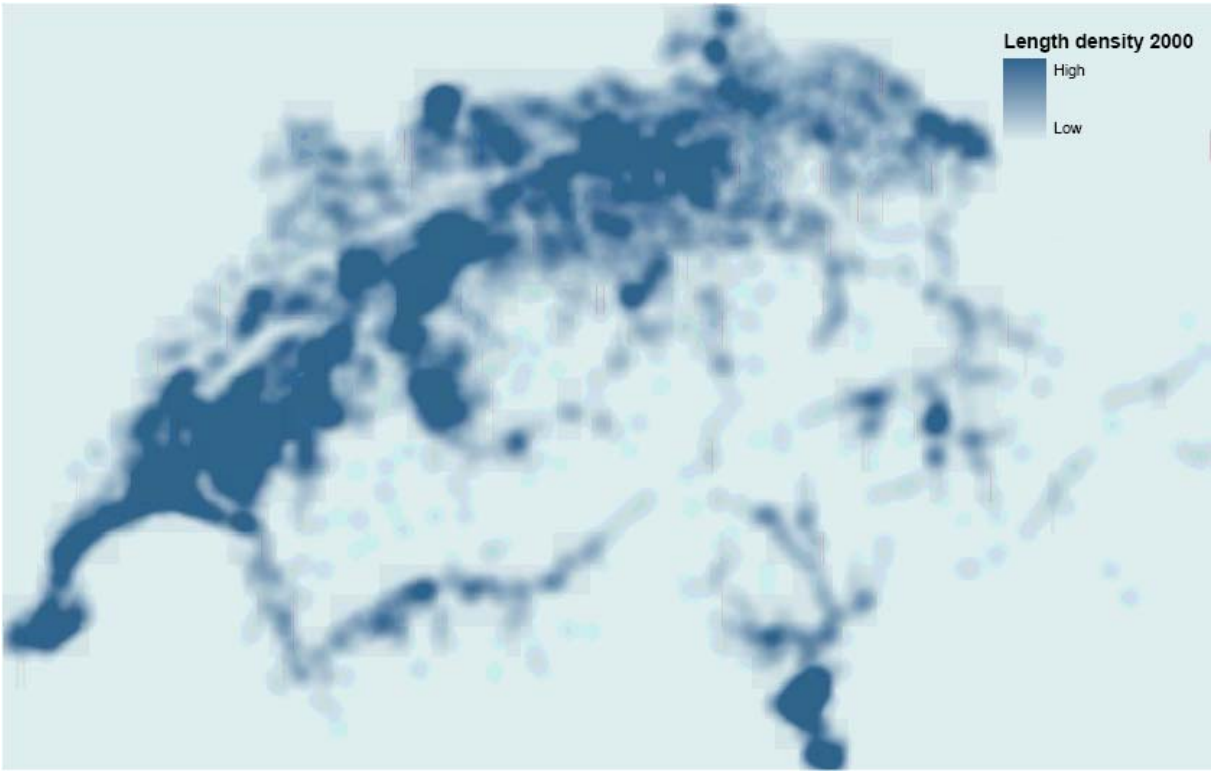


Kernel Density

The approach of calculating densities only for delimited zones has a major disadvantage as the results are spatially limited and may not be used area-wide. The concept of kernel density is therefore applied.

Figure 9 shows the road density distribution for the Swiss road network. The largest agglomerations have the highest values. Though, a meaningful application on vulnerability analysis is imaginable as dense networks parts may respond better on link or node failures. However, as spare capacity and local demand are equally important for vulnerability, only a combination seems to be really promising and further research on the applicability of such density measures is needed.

Figure 9 Kernel density smoothed road densities



4. Conclusion

The review of the recent network analysis literature revealed the node-centric emphasis of this research. In contrast to many other networks, transportation networks have spatial restrictions which has strong implication on the network topology. An unweighted road network shows therefore always regular network patterns. The presence of zones with different importance and link speeds depending on capacity reveals the necessity of the extension of widely used network topology measures by adding a weighting scheme. The application of such measures on transportation networks revealed that these are already well known with different names as for examples like closeness centrality (accessibility) or betweenness centrality (loads) show.

However, the application of further network topology measures on different network states between 1950 and 2000 revealed interesting temporal aspects. During these years, the network growth was restricted mainly to freeways whose development shows the well-known characteristic s-curve shape. Due to more and more spatial and environmental constraints, the net length of tunnels of is still increasing while the rest of the freeway network has reached its growth limits. Concerning the topological measures proposed by Xie and Levinson the Swiss upper-hierarchy network shows interesting temporal characteristic as the network is for a long time constituted out of several subgraphs without circuits, as in several cases the construction of the connecting road section was postponed or suspended due to environmental issues. In absences of urban beltways only regional-scale circuits emerge through the connection of three or more different freeways.

The measures of global centrality measures show a twofold picture. On the one hand, it is very impressive to see how efficient a road network may distribute demand compared to a fully connected network. On the other hand, the measure shows border effects as the negative relation between attractiveness and distance of to nodes is neglected.

Clustering patterns are important characteristics of complex networks as proxy for redundancy. Previous applications of the concept to road networks considered only the direct neighbouring nodes or links neglecting possible capacity limitations which may restrict the redundancy. Therefore a measure incorporating link length and capacity in a given radius is proposed. An ongoing project dealing with vulnerability will address the use of the further measures.

Furthermore, this work showed that the application of network measures as used in the analyses of complex network for transportation network is challenging, because of the complex weighting characteristics which involve capacity and spatial restraints. However, transportation research anticipated the important measure of betweenness (link load) as well as the concept of closeness (accessibility). Clustering measures on the other hand are not widely used for transportation applications yet. Further research on vulnerability of transport

infrastructure might change this, as research in the field of statistical mechanics of complex networks revealed the importance of clustering for the vulnerability assessment.

5. Acknowledgements

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6. Literature

Albert, R. H. Jeong, and A-L. Barabási (1999) Diameter of the World-wide Web, *Nature*, **4**, 131.

Albert, R. and A.-L. Barabási (2002) Statistical mechanics of complex networks, *Reviews of modern Physics,* **74**, 47-97.

Axhausen, K.W., P. Fröhlich and M. Tschopp (2006) Changes in Swiss accessibility since 1850, *Arbeitsberichte Verkehr und Raumplanung*, **344**, IVT, ETH Zürich, Zürich.

Bailey, T. C. and A. C. Gatrell (1995) *Interactive Spatial Data Analysis*, Essex, England Longman.

Barabási A.-L., H. Jeong, Z. Neda, E. Ravasz, A. Schuber, T. Vicsek (2002) Evolution of the social network of scientific collaborations, *Physica A*, **311**, 590-614.

Barabási, A.-L. and E. Bonabeau (2003) Scale-Free Networks, *Scientific American*, **288**(5).

Camacho, J., R. Guimera, L.A.N: Amaral (2002) *Phys. Rev. Lett*, **88**, 228102.

Crucitti, P., V. Latora and M. Marchiori (2004) A topological analysis of the Italian electric power grid, *Physica A*, **338** 92-97.

Crucitti P, V. Latora and S. Porta (2006) Centrality measures in spatial networks of urban streets, *Physical Review E,* **73**, 036125.

Erath, A. and Ph. Fröhlich (2004) Geschwindigkeiten im PW-Verkehr und Leistungsfähigkeiten von Strassen über den Zeitraum von 1950-2000, *Arbeitsbericht Verkehrund Raumplanung*, **183**, Institut für Verkehrsplanung und Transportsysteme (IVT),ETH, Zürich.

Erdõs, P. and A. Renyi (1959) On random graphs, *Publ.Math,* **6**, 290-297.

Faloutsos, M., P. Faloutsos and C. Faloustos (1999) On power-law relationships of the Internet topology, *Computer Communications Review*, **29**, 251.

Fischer.S. and A. Volk (1999) Chronologie der Schweizer Autobahn, in *Die Schweizer Autobahn* (M. Heller and A. Volk, eds.) Museum für Gestaltung, Zürich.

Fröhlich, P. and K.W. Axhausen (2005) Sensitivity of accessibility measurements to the underlying transport network model *Arbeitsberichte Verkehrs- und Raumplanung*, **245**, IVT, ETH Zürich, Zürich.

Fröhlich, Ph., T. Frey, S. Reubi and H.-U. Schiedt (2004) Entwicklung des Transitverkehrs-Systems und deren Auswirkung auf die Raumnutzung in der Schweiz (COST 340): Verkehrsnetz-Datenbank, *Arbeitsbericht Verkehrs- und Raumplanung*, **208**, IVT, ETH Zürich, Zürich.

Freeman, L.C. (1979) Centrality in social networks: conceptual clarification, *Social Networks*, **1**, 215-239.

Freeman, L. C. (1977) A set of measures of centrality based on betweenness, *Sociometry,* **40**, 35-41.

Grübler, A. (1990) The rise and fall of infrastructures:dynamics of evolution and technological change in transport. *Physica-Verlag*, Heidelberg.

Hargett p. and Chorley, J.C. (1969) *Network Analysis in Geography*, Butler and Tanner Ltd., London.

Hillier, B. and Hanson, J. (1984). *The Social Logic of Space* Cambridge University Press.

Garrison, W.L. (1960) Connectivity of the Interstate Highway System, *Regional Science Association,* **6,** 121-137.

Garrison, W.L. and Marble, D.F. (1962) The Structure of Transportation Networks. *Army Transportation Command,* **62-II**, 73-88.

Gätzi, M. (2004) *Raumstruktur und Erreichbarkeit am Beispiel der Schweiz zwischen 1950 und 2000*, Diploma Thesis, IVT, ETH Zurich, Zurich.

Geurs, K. T. and J. R. Ritsema van Eck (2001) *Accessibility measures: review and applications*, RIVM report, 408505006, National Institute of Public Health and the Environment, Bilthoven.

Gibbons, A. (1985) *Algorithmic Graph Theory*, Cambridge University Press, Cambridge.

Jeong, H., B. Tomber, R. Albert, Z.N. Oltvai, and A.-L. Barabasi, "The large-scale organization of metabolic networks", Nature, **407** 651 (2000).

Jiang, B., C. Claramunt (2004) Topological analysis of urban street networks, *Environment and Planning B*, **31** (1), 151-162.

Kanskey. K. (1969) Structure of transportation networks: relationships between network geometry and regional characteristics, Univ. of Chicago, Chicago.

Latora, V. and M. Marchiori (2002) Is the Boston subway a small-world network?, *Physica A,* **314**,109 – 113.

Latora, V. and M. Marchiori (2001) Efficient beahviour of small-world networks, *Physical Review Letters*, **87**, 198701.

Levinson (2005) The Evolution of Transport Networks, in *Transport Strategy, Policy and Institutions* (D. Hensher, ed.) Elsevier, Oxford.

Marshall S. (2005) Streets & Patterns, *Spon Press*, New York.

Porta, S. P. Crucitti, and V. Latora (2006), The network analysis of urban streets: A dual approach, *Physica A,* **369** 853–866.

Rietveld, P. and F. Bruinsma (1998*) Is Transport Infrastructure Effective?*, Springer Verlag, Berlin.

Sabidussi, G. (1966) The centrality index of a graph, *Psychometrika*, **31**, 581-603.

Shannon, C.E. (1948) A Mathematical Theory of Communication, *Bell System Technical Journal,* **27**, 379-423 and 623-656.

Silverman, B.W. (1986) Density Estimation for Statistics and Data Analysis, Chapman and Hall, New York.

Tschopp, M., P. Fröhlich and K.W. Axhausen (2005) Accessibility and spatial development in Switzerland During the last 50 years, in D.M. Levinson and K.J. Krizek (eds.) *Access to Destinations*, 361-376, Elsevier, Oxford.

Vragovic, I. E. Louis and A. Diaz-Guilera (2004) Efficiency of informational transfers in regular and complex networks, *http://orxiv.org/abs/cond-mat/0410174*.

Vrtic, M., Fröhlich, P. Schüssler, N. Axhausen, K.W. Dasen, S., Erne S., Singer, B., Lohse, D. and Schiller, C. (2005): Erzeugung neuer Quell-Zielmatrizen im Personenverkehr, Bundesamtes für Raumentwicklung (ARE), Bern.

Wardrop, J. G. (1952) Some theoretical aspects of road traffic research, *Proceedings, Institute of Civil* Engineers *II*, **1**, 325-378.

Watts D.J., S. H. Strogatz (1998) Collective dynmamics of small world networks, *Nature*, **410** 268.

Xie, F. and D. Levinson (2007) Measuring the structure of road networks, *Geographical Analysis*, **39** (3), 336–356.