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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 network densities 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. It could be showed that the proposed measures are able to characterise the growth of the Swiss road network. To proof the use of local density measures to explain the robustness of a network however needs further research.

Keywords Transport network topology · Network efficiency · Highway network development · Kernel density

Contribution to the special issue of Networks and Spatial Economics on the topic of "The Evolution of Transportation Network Infrastructure"

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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; Kanskey 1969; Hargett and Chorley 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 (Marshall 2005). However, further research emerged from fields which are not directly linked to transport. The modelling of complex systems as networks 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. (2002) documented seven food webs.

Although transport infrastructure are the networks of daily life, only little analytical research can be found for transport networks. A basic difference to other, often social networks is that transport 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 they are strongly constrained which has consequences for the degree distribution (the number of edges every node is connected to) which is often used to classify complex networks. Furthermore, the number of long range connections is limited as well, as 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 limits these networks to be not scale-free (Barabási and Bonabeau 2003).

Hence, the aim of this paper is to gather existing and propose new approaches of network analysis which consider the peculiarities of transport infrastructure networks. Thereby, a section is devoted to measures which are able to monitor the growth of such networks. Therefore, this work compares networks not only horizontally but longitudinally by comparing the network characteristics from 1950 to 2000 in 10 year steps and discusses the relevance of these measures to transport policy issues.

The remainder of the paper is organised as follows: Section 2 discusses recent developments in the analysis of transport infrastructure networks and their application to the infrastructure development in Switzerland. Section 3 provides an overview of the measures while Section 4 presents the data used. Section 5 describes the development of the network using the measures selected and Section 5.3 describes qualitatively the local robustness of today's network using new approaches. We conclude with Section 6 which provides an assessment of the measures and indicates further research needs and possible applications of transport network analysis.

2 Attempts at graph theoretical analysis of transport 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 transport networks. In transport networks the hierarchy is given by the functional characteristics of the links. The functional classification reaches from local streets with access to the adjoining 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 of 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. If a two circuits share common links it is named a web with the measure webness equally defined as for the ringness. The sum of ring- and webness equals the circuitness which in turn defines the treeness as the percentage of the arterial network that does not belong either to a ring or a web.

These measures are calculated here for the upper levels of the Swiss network (the first n of the m hierarchy levels). The changes over time are traced by for each decade since 1960 and for the present state (2005) and the forecast network state in 2020.

A further attempt to describe transport networks was undertaken by Jiang and Claramunt (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. (2006b) 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 similar approach using continuity is Hillier's space syntax (Hillier and Hanson 1984) which measures by how many changes of direction the rest of the network is reachable. The result is the so-called integration value which represents how integrated or central a given link is in the network. It could be shown that this integration index is linked to traffic (Hillier 1996). The space syntax approach is mainly used for urban networks and has the same shortcoming of the definition of street continuation rules as well as the omission of metric information as the approach of Porta et al. (2006b). 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 (Freeman 1977, 1979). They proposed that transport networks have to be analysed as weighted networks, whereas the weights are the length of the edges.

Motivated by the idea that the efficiency of spatial networks in distributing information might be measured by comparing the length of the shortest paths between (Latora and Marchiori 2001; Chalasani et al. 2005) 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 and revealed remarkably high values of efficiency. To describe the ability of networks to respond to link failures Latora and Marchiori (2001) introduced the term local efficiency: the path distances between neighbours of a given node passing only through other elements than i in the subgraph of direct neighbours of i.

However, none of these approaches considered the demand on the transport networks although for transport engineers capacity, travel demand and speed/travel time are as important as the length of a link. Therefore the weighting in this paper is extended and is therefore twofold, covering not only links and nodes but also demand: The link weight may be 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.

3 The proposed transport network measures

3.1 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. Hargett and Chorley (1969) described however two basic structures for planar transport 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. Gibbons (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.

$$\phi_{\mathrm{Ring}} = \frac{\text{Total length of arterials on rings}}{\text{Total length of arterial}} \tag{1}$$

$$\phi_{\mathrm{W}eb} = \frac{\text{Total length of arterials on webs}}{\text{Total length of arterial}} \tag{2}$$

$$\phi_{\mathrm{Circuit}} = \phi_{\mathrm{Ring}} + \phi_{\mathrm{Web}} \tag{3}$$

$$\phi_{\mathrm{Tree}} = 1 - \phi_{\mathrm{Circuit}} \tag{4}$$

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 upper levels Swiss networks.

3.2 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, 1979):

$$C_i^D = \frac{k_i}{N-1} = \frac{\sum\limits_{j \in N} a_{ij}}{N-1} \tag{5}$$

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 transport networks (but not for those of air transport) degree centrality is limited due to spatial constraints, at least as long as nodes represent junctions. However, for nodes that represent 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).

$$C_C = \frac{N-1}{\sum\limits_{j \in N; i \neq j} d_{ij}} \tag{6}$$

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:

$$C_i^C = \sum_{j \in N, i \neq j} \frac{\sum\limits_{i,j \in N, i \neq j} W_j TT_{ij}}{\sum\limits_{j \in N, i \neq j} W_j} \tag{7}$$

where W_j is the weight of demand zone j and TT_{ij} 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; 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 transport 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; Fröhlich and Axhausen 2005). Therefore, closeness centrality is not pursued here.

3.3 Betweenness centrality

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

$$C_i^B = \frac{1}{(N-1)(N-2)} \sum_{j,k \in N; j \neq k; j; k \neq i} \frac{n_{jk}(i)}{n_{jk}}, \tag{8}$$

with n_{jk} as the number of the shortest path between the nodes j and k and $n_{jk}(i)$ as the number of path between j and k which pass trough node i. 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 transport-aware equivalent for betweenness centrality is only available for the year 2000.

3.4 Efficency and straightness centrality

3.4.1 Global efficieny

Latora and Marchiori (2001) proposed to measure the efficiency of spatial networks distributing information by comparing the length of the shortest paths between nodes with the crow-fly distance. Their straightness centrality $\left(C_i^S\right)$ and efficiency centrality $\left(C_i^E\right)$ and are defined as:

$$C_i^S = \frac{1}{N-1} \sum_{j \in N; j \neq i} \frac{d_{ij}^{\text{crowfly}}}{d_{ij}} \tag{9}$$

$$C_i^E = \frac{\sum_{j \in N; j \neq i} \frac{1}{d_{ij}}}{\sum_{j \in N; j \neq i} \frac{1}{d_{ij}^{\text{crowfly}}}} \tag{10}$$

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 $\left(C_i^W\right)$. Such an extended attempt might be even more essential if large road networks (Porta et al. 2006b) 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 Eq. (11).

$$C_i^{ws} = \frac{\sum_{j \in N; j \neq i} W_j \frac{TT_{ij}^{\text{crowfly}}}{TT_{ij}}}{\sum_{j \in N, i \neq j} W_j} \tag{11}$$

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.

3.4.2 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 and might be therefore interpreted as a proxy for the local robustness of the network against link failures. This application seems to be too restrictive since such an approach only considers triangles to deliver local alternatives in case of a link failure. The same applies to the measure of Latora and Marchiori (2001) mentioned in section 2. Two different types of measures are introduced to overcome these limitations: First, the shortest path between the two nodes of a given link is calculated after this link has been removed. Since it can be assumed that the demand in the case of a link failure will be distributed more widely than only passing along the new shortest path between the two separated nodes a set of measures which describe local network density is assessed. In a radius of 5 km the number of nodes and links, their cumulative length, their cumulative length multiplied by the particular capacity as well as their cumulative length multiplied by the particular free capacity are calculated to describe the networks local ability to reroute demand in case of a link failure. Those figures should characterise the vulnerability of transport networks locally. However, in this work their contribution to the description of local efficiency is qualitative.

4 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 2,896 municipalities and the period since 1850 with networks for 1888, 1910, 1930, 1950 and then every 10 years until 2000 (Fröhlich and Axhausen 2005 and Fröhlich et al. 2004). The data for 2005 is an update of the year 2000 model. The 2020 road network is based on the freeway construction plans of the Swiss Federal Roads Office and updates only the freeway network.

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 decade. 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 network model employs 35 different road types which allows a reasonable differentiation. This approach was found to be in good alignment for the year 2000 with the results of a deterministic user equilibrium (Vrtic et al. 2005).

The assumptions about the mean speeds were based on a substantial review by Erath and Fröhlich (2004) 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, 1990 and 2000.

4.1 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 the literature that macroscopically, the growth of an 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 transport network length by link type and is normalised for the year with the longest network length.

It is obvious that saturation was already reached for trunk roads and local distributors in 1950. Planned as a new network within the existing one the national free- and highway network shows the characteristic s-shaped curve. Interestingly, the curve for tunnels has a time shift of around 10 years compared to the rest of the upper network hierarchy. The length of the car train links is substantially smaller (2005: 92 km) than the free-/highway (2000: 4,063 km) or even the trunk-/regional roads (2000: 42,043 km). Nevertheless, the growth shows similar patterns as the other evolving network segments.

The rail network was decreasing between the years 1960 and 1980 because some minor lines had to close for economic reasons, like the Maggia valley railway. 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 is reasonable to focus on the road network only as the rail network showed only minor extensions since the second world war. However, considering the

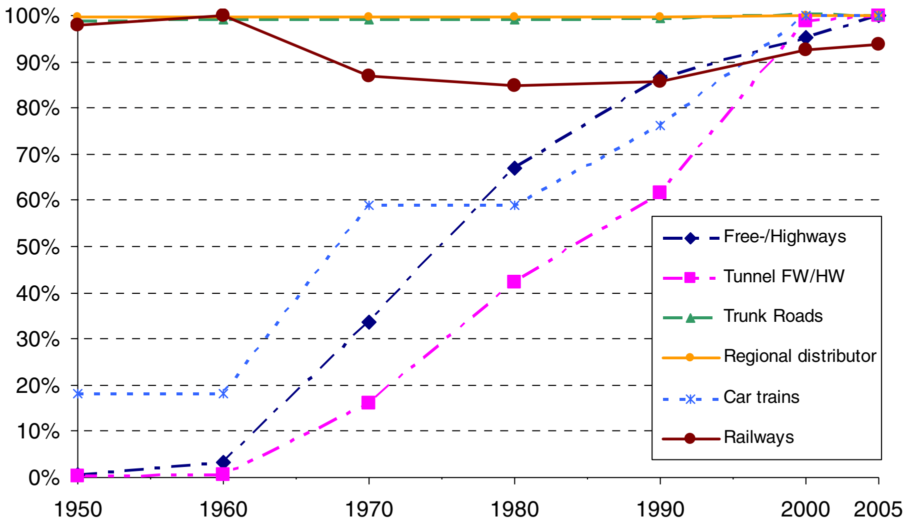

Fig. 1 Normalised length of the Swiss Transport Network 1950–2005. Effective length 2005: *Free-/Highways*: 1,930 km; *Tunnel FW/HW*: 176; *Trunk roads*: 6,195 km; *Regional distributors*: 14,827 km; *Car trains*: 92 km, *Trains*: 5,069 km

development of service density and speed an analysis of the rail network might be an interesting topic for further work.

5 The transport network development in Switzerland 1950–2000

5.1 Network evolution

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 initiative 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 staging (Sandmeier 2008). The sections along the principle east–west as well as north–south axes were prioritised and were to be opened 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 the network hierarchy 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[1]. Only by proposing an alternative including two tunnels a majority were 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 been built. Interestingly, the relevant file with the first motorway network plan has been 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

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

were delayed, like the freeway in the 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 plan for the year 2020, while Table 1 indicates the according measures.

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. Figure 1 shows that 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 its western part will be finished. It is not yet clar, if the first urban beltway will be availale in 2020, as the necessary lake tunnel is still only one option in the long term planning documents. Furthermore, the tunnel is politically rather disputed and detailed 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.

While the aggregated network growth slowed down since 1990 the absolute and relative tunnel growth is unaffected. Ultimately, 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. In addition environmental issues have gained more and more importance in the design for acceptable solutions with low noise emissions. Second, the other main block of projected routes is mainly connecting mountainous regions where tunnels are sometimes the only solution to deal with the topography.

5.2 Centrality measures

5.2.1 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,

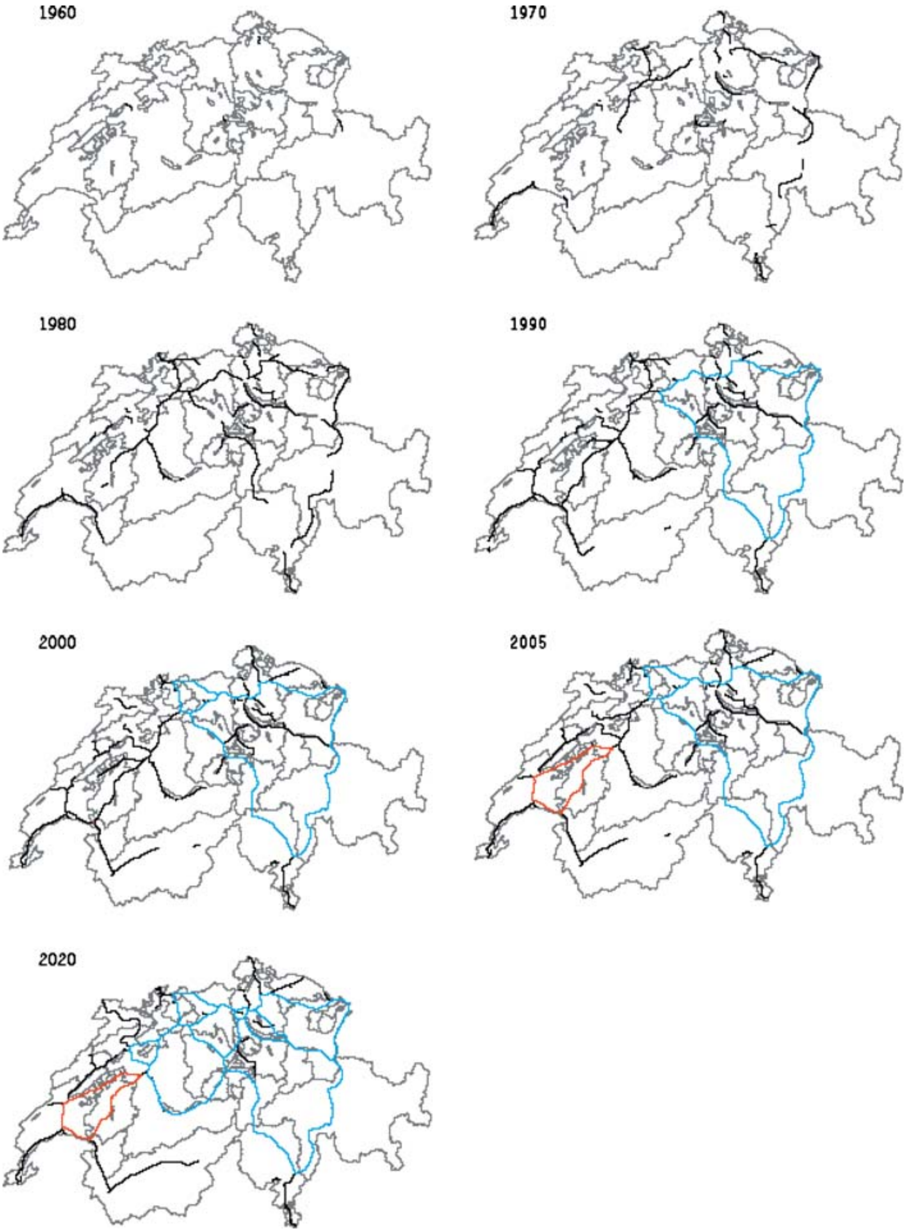

Fig. 2 Development of the Swiss freeway network 1960–2020 (*black*: part of a tree; *blue* part of ring 1; *red*: part of ring 2)

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

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

Year	Length (km)	Percentage tunnel	Percentage tunnel new roads	Sub-graphs	Share of the longest subgraph	Ring-ness	Web-ness	Circuit-ness	Tree-ness
1960	62.50	1.75	1.75	4	0.34	0	0	0	1
1970	678.23	4.14	4.39	26	0.26	0	0	0	1
1980	1,363.96	5.46	6.76	26	0.28	0	0	0	1
1990	1,781.62	6.08	8.11	16	0.90	0.36	0	0.36	0.64
2000	2,014.47	8.65	28.33	13	0.90	0	0.37	0.37	0.63
2005	2,105.99	8.67	2.09	10	0.92	0.11	0.35	0.47	0.53
2020	2,257.32	11.72	54.91	8	0.98	0.15	0.43	0.58	0.42

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 lie mostly in urbanised areas.

5.2.2 Betweenness centrality

As described above, the direct application of betweenness centrality to transport networks is the link or node load. The cumulative link load distribution (Fig. 4) of the Swiss National model (Vrtic et al. 2005) follows an exponential distribution. This is in line with the findings of Porta et al. (2006a) 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. Yerra et al. (2005) even proved the emergence of such network hierarchy as an intrinsic property of transport networks. 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 economically more favourable economically. In the latter case, the demand is

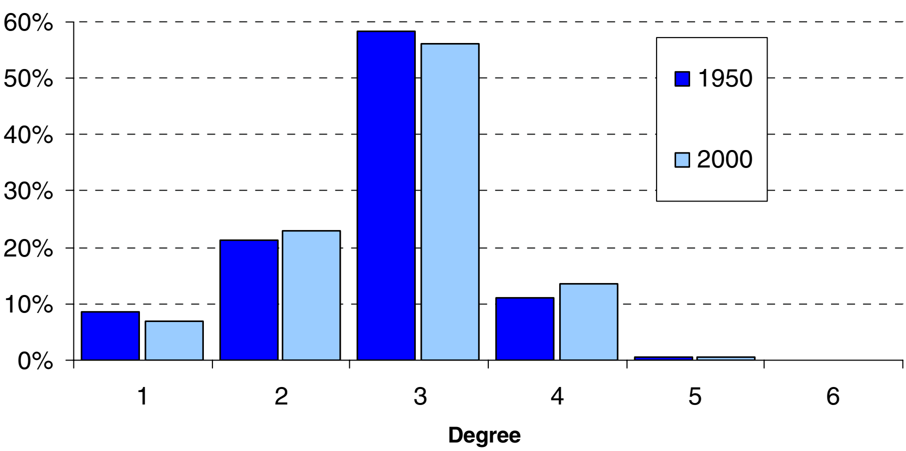

Fig. 3 Degree Distribution: Network 1950/2000 (1950: N=11'004; 2000: N=12'810)

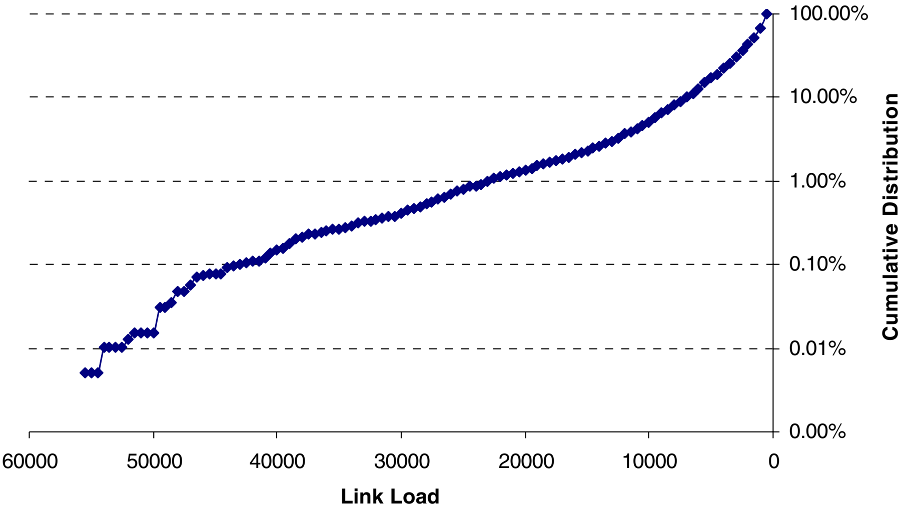

Fig. 4 Cumulative distribution of link loads of the Swiss National Transport Model for 2000

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 should be one explanation for the scale-free distribution.

5.2.3 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 80 km/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, the average efficiency is the result of a weighing reflecting the population (P_i) of each municipality:

$$E_{\mathrm{Net}} = \frac{\sum_i C_i^{ws} \cdot P_i}{\sum_i P_i} \tag{12}$$

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 at 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 to 2000 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 into higher travel speeds and the network was reaching its capacity limits at various locations resulting in higher travel times.

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

Nevertheless, one can ask if the network was expanded in the right 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.

As only few values are found in the literature, the comparison of the values is restricted to the findings of Latora and Marchiori (2002). 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

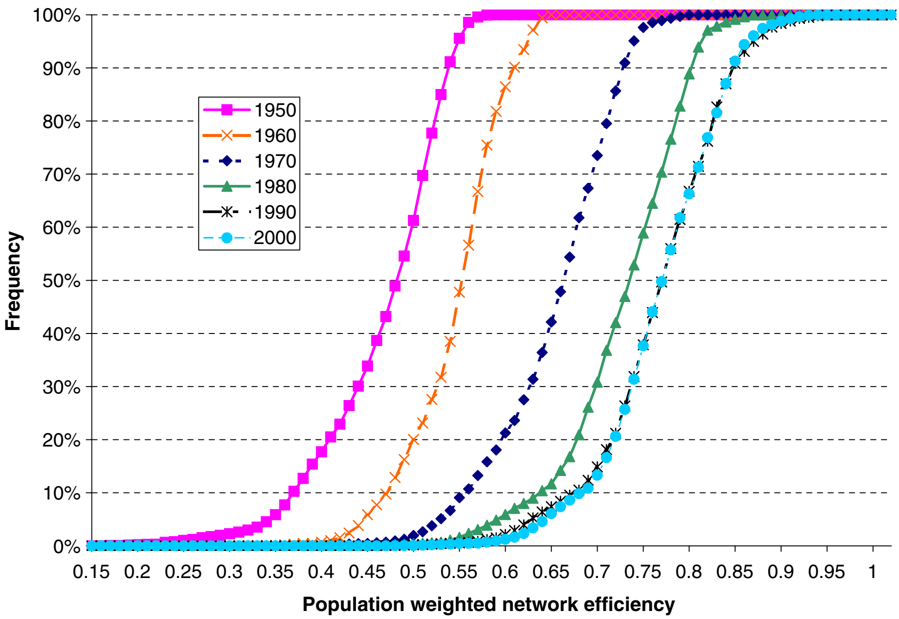

Fig. 5 Cumulative distribution of the Swiss network efficiency on municipal level 1950–2000

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 fitted by a normal distribution.

The spatial distribution of the network efficiency (Fig. 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 these areas have a different scale and cover only major roads plus have 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 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.

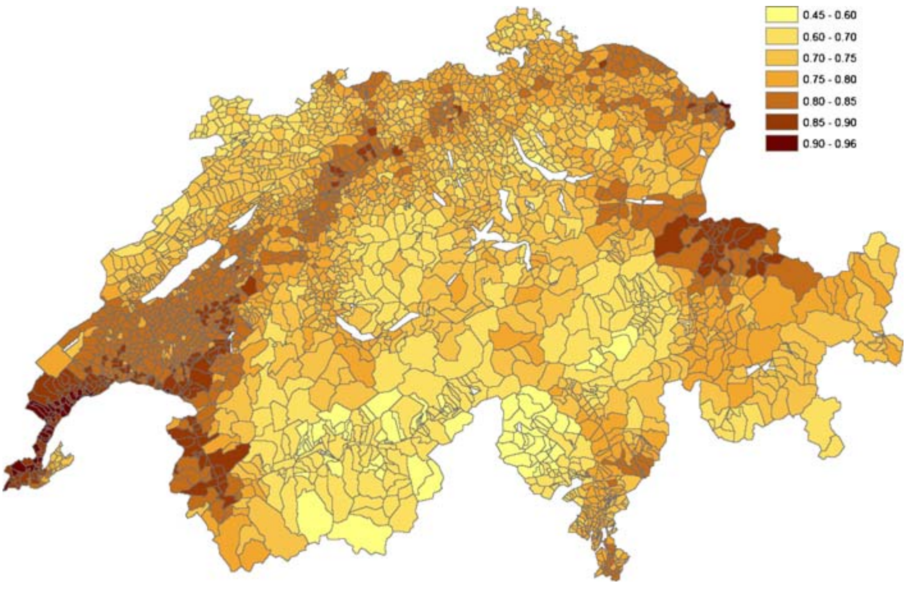

Fig. 6 Municipal network efficiency, 2000

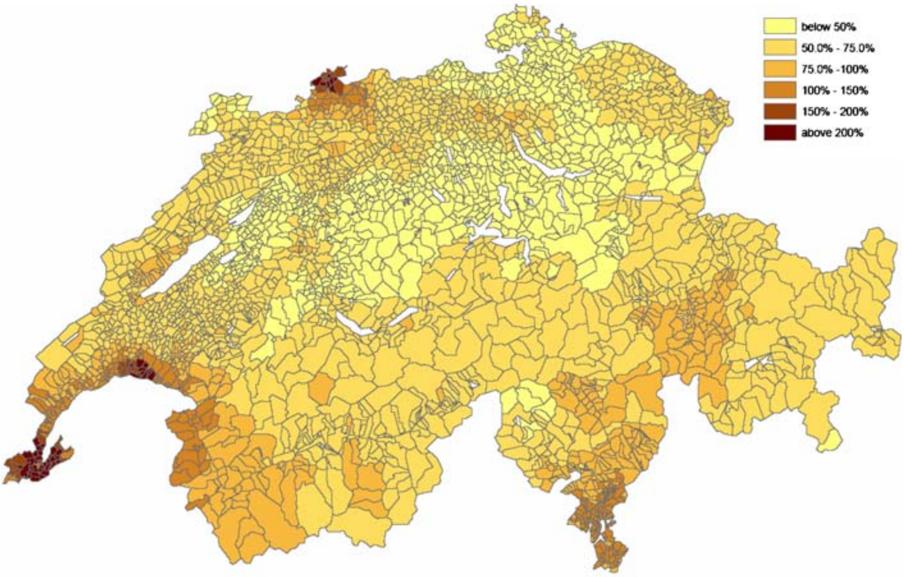

Fig. 7 Growth of network efficiency 1950–2000

5.3 Local efficiency

5.3.1 Growth of road and capacity density

The results shown in Fig. 1 suggest that road density has grown only along the newly constructed freeway corridors. In contrast to road density, an increase in capacity is possible even without new alignments due to the changes in 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 5 km 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. The growth of length density and capacity density is illustrated in Fig. 8.

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. Outside these corridors, the development of road and capacity density is different: Whereas effects of technological advance in vehicle manufacturing raised the capacity globally, additional roads are limited 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 associated with an enormous amount of data collection, but would be essential when analyses involving local roads were envisaged.

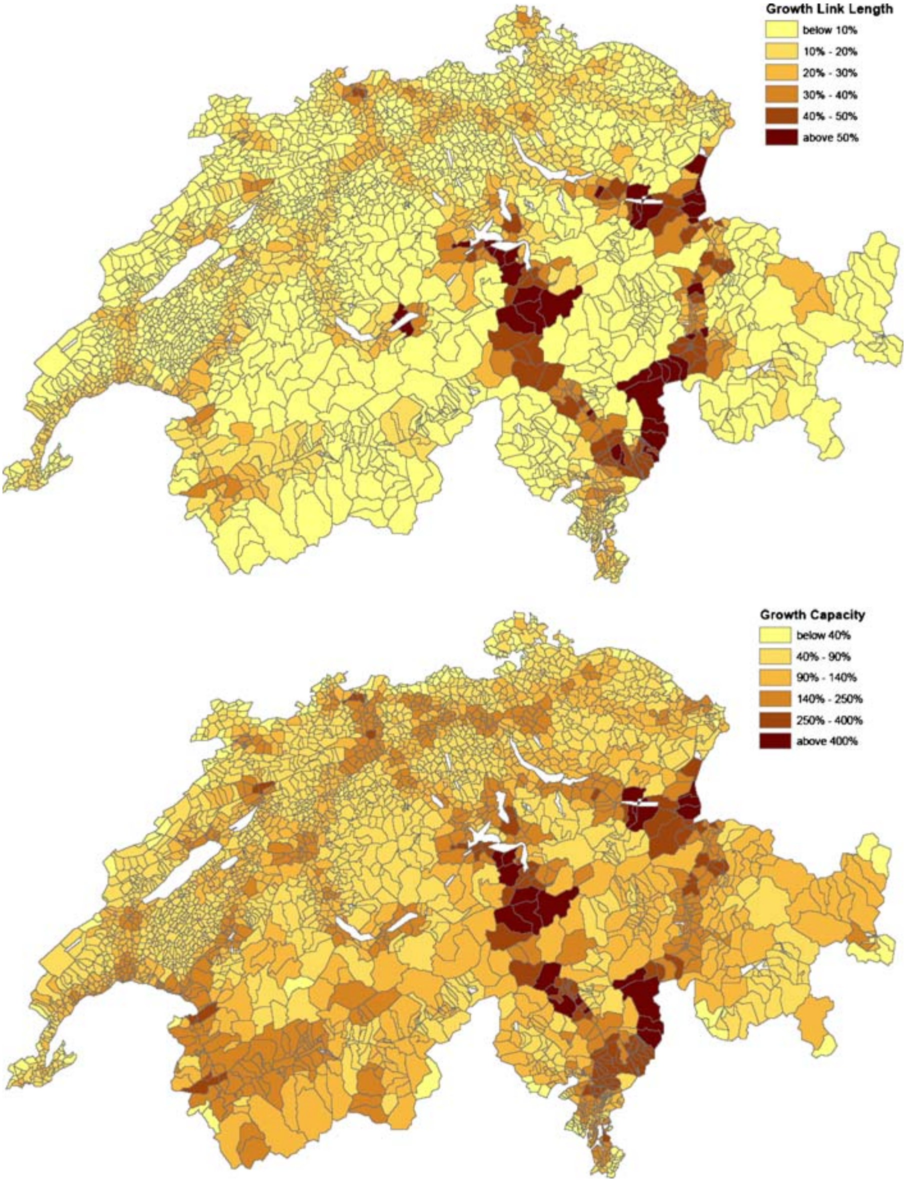

Fig. 8 Growth of road length and capacity (Switzerland, 1950–2000)

5.3.2 Local density figures

It is reasonable to assume that dense networks have a higher ability to respond to link failures smoothly and to distribute demand more efficiently. As our aim is to investigate the link between density and robustness here, only the 2005 network is used. The densities are calculated for each link to avoid spatial smoothing inherent in areawide calculation.

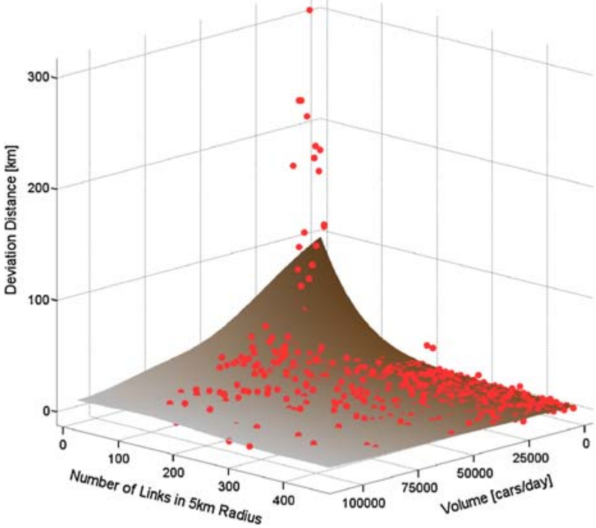

Fig. 9 Connection between volume, link density and shortest deviation

Figure 9 shows the relation between the number of links in a radius of 5 km of a given link, the length of the shortest path between the two nodes of this link after its removal and its flow in the prior state. It becomes clear that with the link density only an upper limit for the shortest deviation may be defined. Interestingly, links with high deviation length are without exception only little travelled which is meaningful for the policy analysis of network robustness.

However, it was argued before that besides the shortest deviation also the local spare capacity density is crucial for a network to be robust, especially in areas with high travel demand. The scatterplot of the number of links within a 5 km radius and the cumulative product of length and capacity (Fig. 10) shows a linear correlation (with a certain variance), as expected. However, when this is plotted against the spare capacity this linearity disappears for higher numbers of links. This shows that the links in areas with higher road infrastructure density are more often used, reflecting a different travel demand and road supply (equilibrium) point. Concerning vulnerability this has strong implications: In less dense regions the average volume/capacity ratio lies around 10–20% which minimises the likelihood of capacity related problems after a link failure. Since traffic volumes increase with higher link density the additional free capacity to absorb the rerouted traffic decreases after a certain link density. Combining both figures and remembering the hierarchy (Yerra and Levinson 2005) of the link volumes it becomes clear that not those links with highest deviations in more remote parts of the network but those with high volume in dense parts of the network with high demand seem to be the most vulnerable. This hypothesis will be tested in an ongoing project which calculates equilibrium states for failure scenarios and compares the results with those of a network in initial state. There other radii than 5 km will be tested as well.

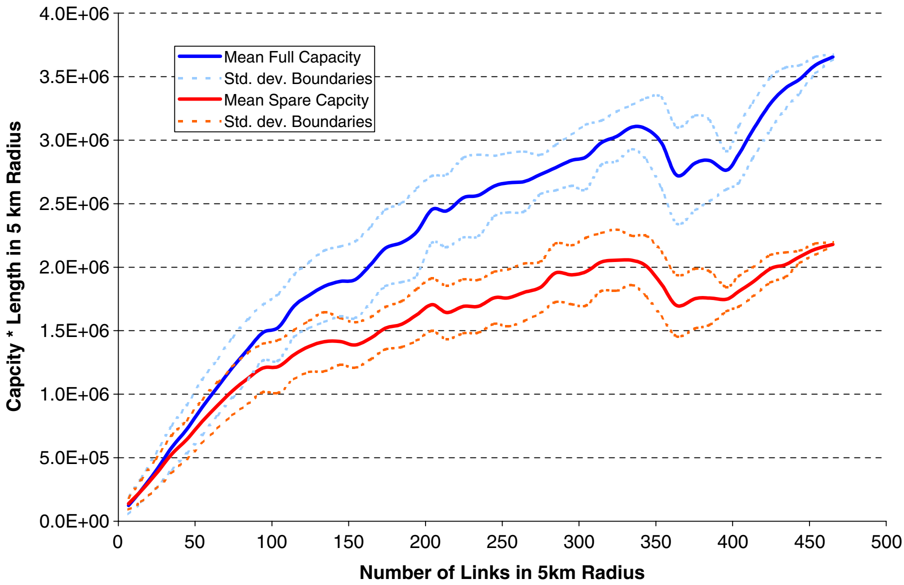

Fig. 10 Comparison of link and capacity density (Switzerland 2005)

6 Conclusion

The review of the recent network analysis literature revealed the node-centric emphasis of this research. In contrast to many other networks, transport networks have spatial restrictions which has strong implication for 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 require the extension of previously used network topology measures by adding a weighting scheme. Such measures of transport networks are already well known under 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 showed 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 (2007) the Swiss upper-hierarchy network shows interesting temporal characteristic as the network was for a long time formed out of several subgraphs without circuits, as in several cases the construction of the connecting freeway section was postponed or suspended due to environmental issues. In the absence of urban beltways only regional-scale circuits emerge through the connection of three or more freeways.

The measures of global centrality 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 transport network is challenging, because of the complex weighting characteristics which involve capacity and spatial restraints. However, transport research anticipated the important measure of betweenness (link load) as well as the concept of closeness (accessibility). Local density measures on the other hand are not widely used for transport 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 local density (known as clustering) for the vulnerability assessment.

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