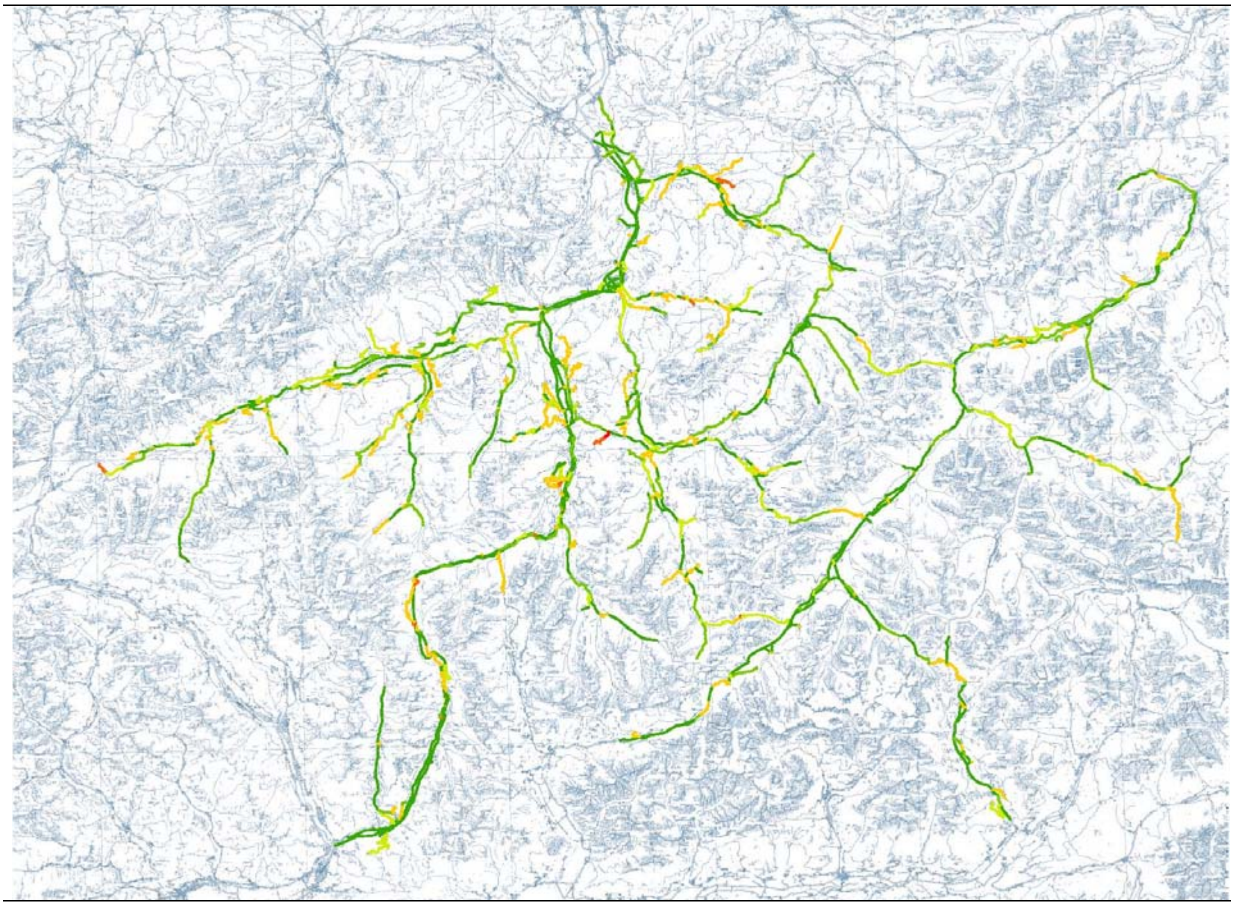

A method for estimating highway gradients and curvatures for capacity determination

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A method for estimating highway gradients and curvatures for capacity determination

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Abstract

In transport assignment models the capacity assumed for the links is a central input variable. The paper describes a methodology to calculate the gradients and curvatures of highway network links using a Digital Elevation Model (DEM) to improve link capacity determination.

The found results are compared with empirical data, and possible ways to improve the results further are outlined.

Keywords

GIS – Gradient – Highway – Curvature – Capacity – 4th Swiss Transport Research Conference – STRC 2004 – Monte Verità

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1. Introduction

Transport network models consist of nodes and links. Links have the following main attributes: capacity, free flow velocity, length and the corresponding capacity restaint function. In the case of nodes, the main attributes are capacity and time loss for the different turning movements. When a model covers a large area, e. g. Switzerland, generally only the attributes of the links are considered. Furthermore, it is very costly to collect all the information about nodes. In addition, nodes of this scale act as a summary of all the minor nodes not directly represented. In the case of a model covering a city or a smaller region the attributes of the main nodes should be estimated and modelled in detail.

One of the limiting factors of highway link capacity is the gradient. The gradient is considered in the calculation of the capacity for road design projects, but in road transport assignment models it is mostly ignored. Moreover, the gradient is also useful in road freight assignment models, as especially, heavy lorry traffic is more sensitive to the hilliness of routes compared with car. Furthermore, the data can help to improve the calculated air pollution due to road transport, because of the higher emission rates of vehicles on slopes.

The remainder of this paper is organised as follows. Chapter 2 reviews the capacity of highways, as well as empirical data for the velocity of lorries on uphill stretches. Next, Chapter 3 describes and analyses the approach used in the paper. Finally, Chapter 4 critically examines the results.

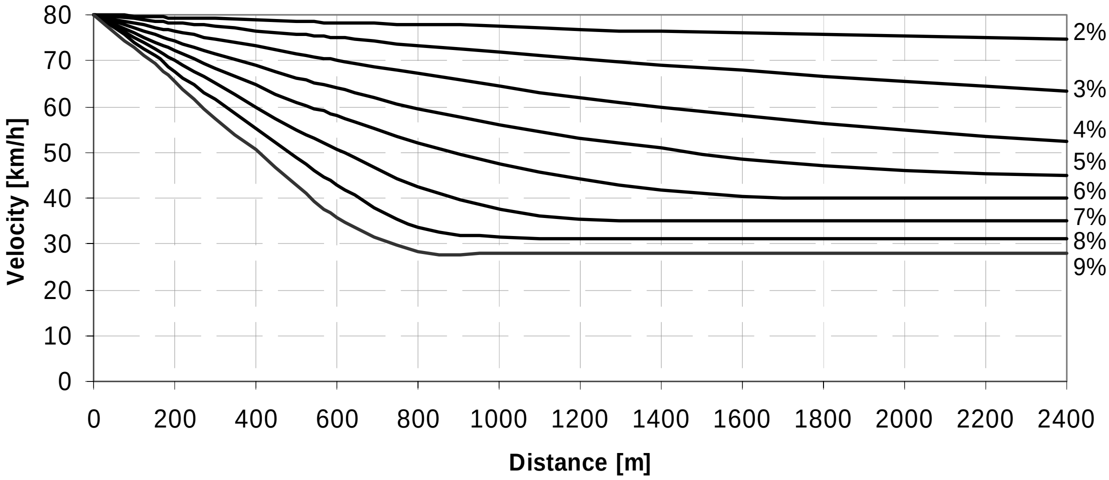
2. Capacity calculation

The following description of the capacity calculation for highways follows the German *Handbuch für die Bemessung von Strassenverkehrsanlagen* (FGSV, 2001). It is the current manual for highway design and uses vehicle and highway properties, which are similar to the Swiss ones. There are four main factors, which influence the capacity of highways, when the node capacity is not the limiting factor:

- number of lanes: a standard rural highway consists of one lane per direction. If there are on the whole link two lanes per direction the capacity should be calculated differently, because of the different overtaking possibilities.
- road type: the rural highways can be separated into main roads (few intersections), connection roads and secondary roads (many intersections).
- gradient of a highway: The steepness of a grade slows the vehicles, primarily the lorries. This slows down the whole traffic stream and the capacity decreases. On motorways, the impact of the gradient on the capacity is considered for cars, because of the better overtaking possibilities.
- Curvature of a highway: the curvature influences the possibility of overtaking through its impact on sight distances.
- the share of heavy-vehicle traffic: Due to the fact that heavy-vehicles have different driving performance, they influence the capacity heavily.

The number of lanes and the road type are normally available from the road authority. For the gradient and for the curvature there are classifications in FGSV (2001): five classes for the former and four for the latter. The important variable for the gradient classification is the mean speed of the v_{15} lorry (15 % of the lorries are slower). This speed is a proxy for the speed of a heavy fully loaded lorry. The concept goes back to Brannolte (1980). This is calculated for links longer than 300m. It is assumed, that the gradient and its length influence the velocity of the heavy lorries. A steep grade with only a short length does not influence the speed. In Figure 1 shows the v_{15} as a function of the gradient and the length of the section. The speed thus obtained is added to the speed before the section (normally the speed limit of 80 km/h) and divided by 2 to get the mean velocity. In the case that crawl speed is reached, there is no averaging.

Figure 1 Velocity profiles for the design lorry by gradient and length of slope



Source: Koy and Spacek (2003), 59

Table 1 shows the lowest mean velocity of standard design lorry with the corresponding gradient category.

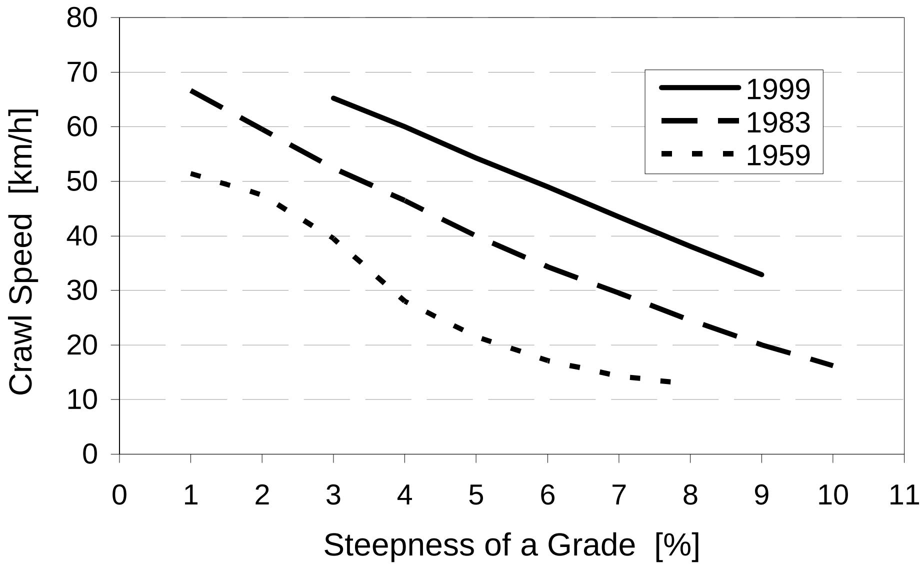
Table 1 Classification of steepness on highways

steepness category	lowest mean velocity of standard design lorry on a link
1	> 70
2	55-70
3	40-55
4	30-40
5	< 30

Source: FGSV (2001), 5-6

Figure 2 shows the development of the crawl speed of heavy lorries over the last 40 years in Switzerland. The huge improvement due the stronger motorisation of the freight transport vehicles is obvious. Furthermore, the introduction of lower speed limits led to a smoother traffic flow and higher capacities (Erath and Fröhlich, 2004).

Figure 2 Development of crawl speed for heavy lorries between 1959 and 1999



Source: Erath and Fröhlich (2004), 81

3. GIS Methodology

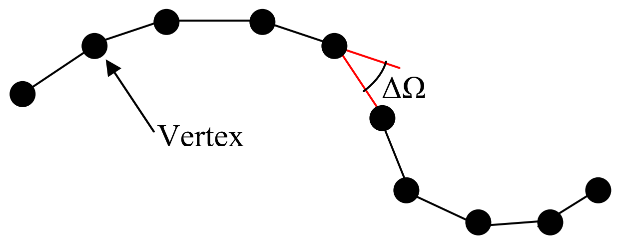
3.1 Curvature

The FGSV (2001) classifies the links into 4 different classes by their curvature:

Class 1: 0-75 gon/km
Class 2: 75-150 gon/km
Class 3: 150- 225 gon/km
Class 4: > 225 gon/km

A line defined by 3 or more points is called a polyline. In GIS terminology a point is also called a vertex. Vertexs connected together with small straight lines, describe a bending line or in this case the shape of a street. To measure the curvature of every street the angle difference ($\Delta\Omega$) in gon between the points was calculated and added together (compare Figure 3). The sum of the angle differences divided by the length of the link in kilometre gives the curvature of the link.

Figure 3 Determination of curvature



The distance between the points depends on curvature of the link. On links with stretched alignments there is a point every 200 to 250 meter, on more winding links there is a point every 125 m and on very winding links the distance goes down to 75 m. The work was conducted with the data from the MicroDrive dataset from the company MicroGIS.

3.2 Gradient of highways

The gradient of a highway can be a limiting factor of the capacity, as described in Chapter 2. This means, if a street is steeper than 2% over a certain section, the traffic slows down. Table 2 shows the formulas needed to calculate the velocity on a highway section with a distinct gradient. The equations are estimated using the current vehicle data of Koy and Spacek, 2003. In the equation, x is the length of the section over which the gradient value is constant. If the section reaches a certain length (3rd column in Table 2), the velocity will level off to the crawl speed.

The section with the lowest velocity is finally the standard section for the whole link and can be implemented in the capacity calculation.

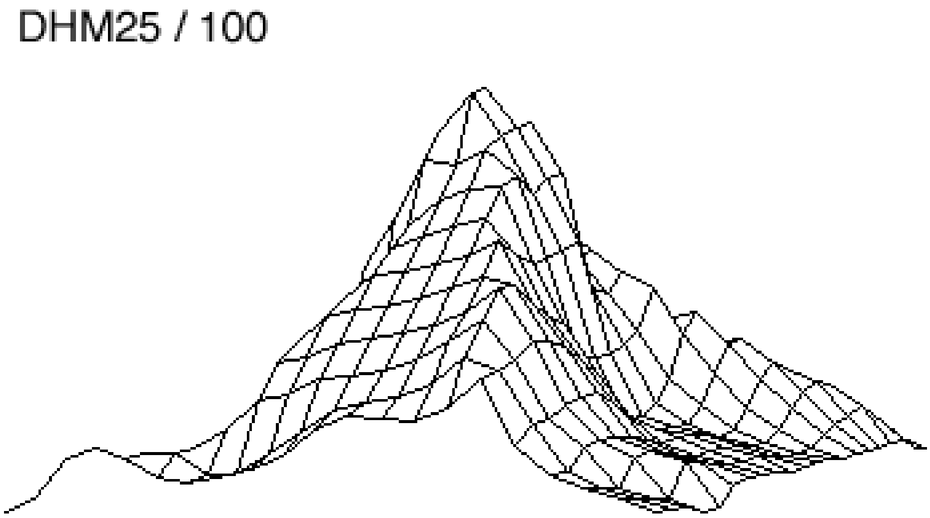
Table 2 Velocity of the standard design lorry for different gradients and length of gradient

Gradient	Equation for the velocity	Crawl speed reached at	Crawl speed
2%	$v = 3 \cdot 10^{-7} x^2 - 0.0029x + 80.0$	2400 m	74.6 km/h
3%	$v = 8 \cdot 10^{-7} x^2 - 0.0089x + 80.0$	2400 m	63.2 km/h
4%	$v = 3 \cdot 10^{-6} x^2 - 0.0184x + 80.0$	2400 m	52.4 km/h
5%	$v = 7 \cdot 10^{-6} x^2 - 0.0304x + 80.0$	2400 m	45.0 km/h
6%	$v = 1 \cdot 10^{-5} x^2 - 0.0453x + 80.4$	1800 m	40.0 km/h
7%	$v = 2 \cdot 10^{-5} x^2 - 0.0643x + 81.2$	1400 m	35.0 km/h
8%	$v = 3 \cdot 10^{-5} x^2 - 0.0828x + 81.9$	1200 m	31.0 km/h
9%	$v = 6 \cdot 10^{-5} x^2 - 0.1095x + 80.1$	900 m	28.0 km/h

Using data from Koy and Spacek (2003), 59

To identify the relevant gradient the highway network (Vrtic, Fröhlich and Axhausen, 2003) is overlaid on the Digital Elevation Model (DEM) of Switzerland. The DEM of Switzerland is a mesh model based on the Swiss National Map with the scale of 1:25 000 (accuracy 1.5 to 10 m) and available as grids which a mesh width of 25 m, 50 m, 100 m, 200 m or 1000 m (Figure 4).

Figure 4 Mesh model (perspective) of the Matterhorn



Source: http://www.swisstopo.ch/en/digital/DHM25.htm

The DEM 100 was used to calculate the street gradients. The streets were split at every mesh border into sections with a length between 0 and 141.42 m, the gradient of each section is calculated (delta height / length of the section). The height of the section's endpoints is determined by the DEM.

A sensitivity analysis revealed that the DEM with mesh width of 25m and 50 m is too accurate to establish the street gradients. The links would be split into very short sections (< 35.35 respectively < 70.7 m) and the subsequent merging process of the short section removes the accuracy gained from the DEM 25 or 50.

The gradient of a section is relevant for the velocity of the standard design lorry, when the section is longer than 250m. Because the velocity assumption by that length for steepest gradient (9%) in the study of Koy and Spacek, 2003, is 60 km/h, what leads to a mean speed of 70 km/h. And that is the boundary between the gradient category 1 and 2.

A merging process was implemented after dividing the street into sections and determining the gradient of the section. The merging process included the following steps:

1. All subsequent sections, belonging to the same link and pointing in the same incline direction in a row are merged together.
2. Sections with a gradient higher than 9% are set to 9%.

3. The gradient of the merged section is the mean of the section's gradients weighted by lengths
4. For all merged sections with a length less than 250m or/and less than 2% gradient, the gradients are set to zero.
5. For the remaining sections the mean of velocity for the standard design lorry is calculated using the equations of Table 2 and assuming a general speed limit at the beginning of the section of 80 km/h. If the length of the merged section is longer than the length until crawl speed is reached, than the crawl speed is used.
6. Finally, the lowest velocity of a section is recorded for the link.

In Table 3 the impact of the gradient classification and the curvature on the capacity per hour with 10% heavy traffic is shown.

Table 3 Capacity (veh/h) of highways depending on the gradient class and the curvature

Curvature (gon/km)	Gradient Class 1	Gradient Class 2	Gradient Class 3	Gradient Class 4	Gradient Class 5
0-75	2370	2295	1965	1590	1230
75-150	2065	2065	1925	1580	1230
150-225	1840	1830	1795	1570	1230
> 225	1770	1760	1740	1570	1230

Source: FGSV (2001), 5-19

4. Review and Conclusions

The methodology described in Chapter 3 was applied to the highway network of Switzerland and compared with measurements of Koy and Spacek (2003). In Table 4, the results for eleven highway links in the metropolitan Greater Zurich area are shown.

Table 4 Comparison of empirical and calculated data of gradients and mean speed of design standard lorry design standard lorry

Location of the link	Measured mean speed of design standard lorry [km/h]	Measured mean speed of design standard lorry [km/h] with the assumption of a general speed	Measured gradient [%]	Calculated mean speed of design standard lorry [km/h]	Calculated gradient [%]
Sihlbrugg-Baar (after village)	61	70	2.6	74	3.7
Bremgarten-Wohlen (after village)	68	73	3.5	72	7.3
Egg-Scheuren	63		4.0	67	4.0
Lottstetten-Rafz (after border crossing)	30	60	4.5	74	3.7
Ottenbach-Zwillikon (after village)	55	68	4.9	65	4.9
Trimbach-Hauenstein (after village)	50	64	5.2	63	6.4
Pfäffikon-Schindellegi	52		6.0	58	6.9
Regensdorf-Zürich (after village)	49	58	6.1/6.5	65	6.0
Birmensdorf-Filderen (after village)	45	62	6.6	65	7.2
Umiken-Unterbözberg	46		7.8	40	6.3
Densbüren-Staffelegg (after village)	44	55	9.5	60	11.9

Using data from Koy and Spacek (2003)

In some cases the mean speed of the standard design lorry is influenced by the speed limit at the beginning of the link, e.g. in a village the speed limit is 50 km/h. But in the calculation a general speed limit of 80 km/h is used. Also a border crossing or a traffic light at the beginning has an impact on the results. Therefore, in Table 4 not only the measured mean speeds of the standard design lorry are given, but also the results for the mean speed with the assumption that a general speed limit of 80 km/h is applied at the beginning of the link (Table 4, third column).

It also has to be considered that the measured links are located in a densely populated area. That leads to a bigger influence of the different speed limits on the results than for the whole of Switzerland. Unfortunately, there is no national database of georeferenced speed limits.

Another point, which influences the accuracy of the gradient calculation, is that the DEM gives the surface height of the natural ground and therefore neglects all the earth works during the construction of a highway. This sometimes leads to steeper gradients than in reality.

A comparison of the curvature data is not possible because of the lack of measurements.

Concluding, it can be stated, that the methodology presented in the paper provides a practical tool to consider the influence of curvature and gradient on the capacity of highway links in transport models.

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