Accessibility Profiles

Measuring Vulnerability and Amendability of Transportation Network

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1 STATE OF THE ART

Gravity and potential-based models have a long standing tradition in geographic studies of interactions. With the incorporation of graph data structures, these models have undergone a substantial improvement in terms of distance (or generalised cost) component, which can be calculated with realistic accuracy and with account for real-life transportation network issues. Combined graph-potential models are primary tool in two domains: transportation studies and geography, with the focus on slightly different questions. The former's interest is mostly in traffic volume, its variability and correlation to areal units assigned as origin and destination (Erlander and Stewart, 1990). Models have been developed starting from pioneer Chicago Area Transportation Study (CATS, 1960) and nowadays highly sophisticated software tools are available commercially (e.g. PTV 2013).

In the context of geography, the focus is less on exact volume of flows and more on the impact of transportation on territory, its population and economy. One of the key concepts here is *accessibility* – the "potential of opportunities for interaction", as originally formulated by Hansen (1959), which can be re-stated as the ability of certain place to provide good transportation for its inhabitants and businesses (or, alternatively, the property of a place to be easily accessed by the outside inhabitants or businesses). Measures of potential-based accessibility invariably stem from potential formula (Isard W., 1960, owing to earlier work of J.Q. Stewart):

$$V_i = \sum_j m_j \, d_{ij}^{-\beta}, \tag{1}$$

where i-th point in space receives a sum of influences of all other objects (indexed by j) of the analysed system. Each influence is proportional to the "mass" m_j of a remote object and inversely proportional to the distance to this object. To express diminishing effect of distance on interaction, many different functional forms have been employed (Taylor, 1971) and this component is usually elaborated separately under the name of distance-decay function or impedance function. Except for power function with negative β parameter, like above, the exponent function exp ($-\beta d_{ij}$) is widely used today.

Contemporary general formula (e.g. Geurs and Ritsema van Eck, 2001)

$$A_i = \sum_{j<>i} D_j \, F(c_{ij}) \tag{2}$$

replaces distance with a generalized cost notion, where travel time, distance or monetary cost can be substituted. Accessibility of i-th object in a system is a sum of influences of all other objects (indexed by j). Each influence is a product of D_j (j-th object attractiveness) and c_{ij} – the cost of travel between i and j reduced by distance decay function F. Depending on study objective, many variables may be used as attractiveness, from specific like healthcare provision indices to general like population or GDP.

Accessibility gives much better insight into transportation network role in socio-economic system then other measures like gross infrastructure density indices (e.g. road density), or isochrone surfaces (*op cit.*). Compared to first group, it does relate the demand for travel to the supply of infrastructure and even particular topology of infrastructure. Compared to second, it does incorporate distance decay concept and accounts for all possible travel destinations (or origins). Also, it has the property of additiveness, so values obtained for singular objects may be legitimately aggregated to wider areal units or the whole system (country) by simple or weighted summation.

A notable feature of potential-based accessibility is that it does, like no other measure, answer the question of *quality* of the transportation system and it does it in most direct way. In contrast to some other policy-related terms like sustainability or equity, the logic of accessibility computation is close to commonsense semantics and the meaning is

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unequivocal – high accessibility is good, low is bad. Thus, potential-based accessibility is a perfect candidate for strategic goal setting, a benchmark or evaluation criterion. Possibly, it can be tied to investment effectiveness appraisal.

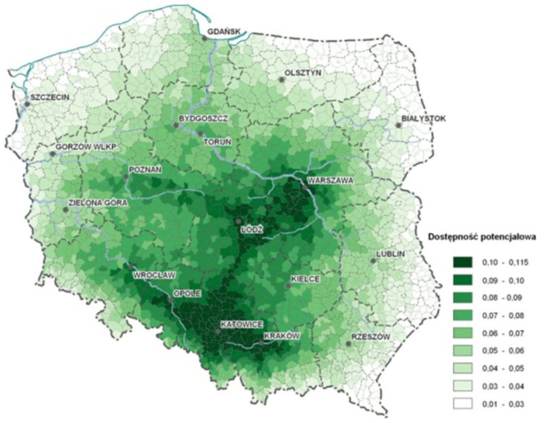

Figure 1: An example of potential-based accessibility in road transportation. *Source: IGiPZ website.*

Starting in 2008, Ministry of Regional Development of Poland become interested in a methodological advances and a software tool capable of evaluating the effects of EU-funded transportation investments. The task was accomplished with the help of tailor-made software for graph-based potential accessibility computation. Shortly after, the next software system OGAM – Open Graph Accessibility Model (Pomianowski, 2012) was developed with significantly extended architecture and features. The system accepts arbitrary graph data set in ESRI shapefile format and allows for formula-based specification of 1) attracting masses, 2) velocity engine and 3) distance decay function. Travel speeds are calculated according to velocity engine specification and used to assign the travel times to graph edges. Then a shortest path algorithm finds the paths for every node-node pair. O-D (origin-destination) matrix found this way is fed into potential calculations. This approach assumes that a transportation network is unsaturated (no alternative paths or traffic load), so the model is applicable only to regional or countrywide level. Total accessibility is computed with weighting, an extra feature is addition of self-potential (see Appendix for explanations).

The most frequently used data and parameter set used in OGAM was designed for private car road transportation modeling and will be referred to as *OGAM Base Model*. OGAM Base Model for December 2014 is comprised of a network of 14400 edges of total length of 65525 km and 2321 nodes corresponding to municipality administrative units (LAU-2) plus 8884 auxiliary nodes (joins, crossings). An attraction mass variable is census population, which also serves as a weighting factor for total (countrywide) accessibility computation. Two exponential distance decay functions are in use, with β parameter of 0.023105 for so called short trips (everyday activity including commuting) with mean of 30 min and 0.005775 for long trips (business, leisure) with mean of 120 min. Travel cost variable is equal to the travel time and is derived from edge length and travel velocity. Travel velocity is based on three factors: road category, road inclination and surrounding population density, combined by a `minimum()` function.

2 RESEARCH PROBLEM

OGAM system has been subsequently used in a series of projects with different networks and parameters. A lot of activity is directed towards tracking accessibility improvement resulting from adding new sections to ever increasing network of motorways in Poland or upgrades made to existing roads (e.g. Rosik and Stepniak, 2013).

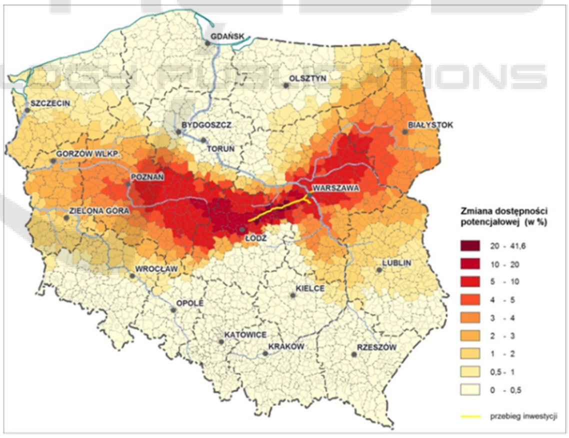

Figure 2: Accessibility change after Warszawa-Lodz motorway construction. *Source: IGiPZ website.*

The system performs well, giving numerical results for pre-change and post-change state of accessibility, which are then imported into GIS and used for map production.

Individual simulations give good view of particular event in network's lifetime and reveal some truth about the role of single edge or group of edges in network connectivity. The scheme is as follows: a change in edge's travel cost (time) gives a response in accessibility measure, both locally (for individual network nodes) and globally.

However, the results lack generality. We are able to test a single improvement by changing a travel time, but we may suspect that other, untested changes on the analysed edge yield different and unexpected changes in accessibility. Though the monotonic relation between travel time and accessibility seems to be beyond discussion, the exact magnitude and shape of this relation in different parts of the network is unexplored. Also, in the current practice, only positive changes have been tested, but exactly the same procedure could be used to simulate negative changes. What is needed is general characteristics of a network edge over the whole range of travel time variability. With fixed edge length this translates to the range of travel speeds. Due to complex formulation and graph involvement, no analytic solution exists to simply derive a range of accessibility values from a single, base value. The only solution is numerical simulation.

In above circumstances, a strong, unifying concept was necessary and it appeared as a *accessibility response profile* (explained in METHODOLOGY section). The other need is of technical nature: existing OGAM software was not designed to run multiple simulations in a systematic way because the complete dataset must be modified and model must be run again for each simulation.

3 METHODOLOGY

Figure 3 illustrates the concept of accessibility response profile. X-axis runs along speed dimension, from 0 value (no traffic) up to maximum allowed speed (in case of Polish Traffic Code, 130 km/h). A special point v_{base} corresponds to actual, current value of speed on the link in the base model. Y-axis runs along accessibility dimension. A special point A_{base} is actual, current value of accessibility computed in the base model. A generic profile runs from zero speed to maximum speed with ever increasing A value and always crosses v_{base} position.

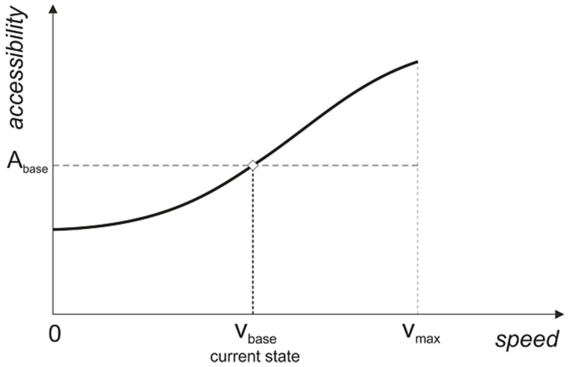

Figure 3: Generic accessibility response profile (exact shape irrelevant).

Two parts of the profile may be distinguished (see Figure 4): left part corresponds to negative change usually related to congestion, accident blocking, construction works or even complete exclusion from traffic. This is the *vulnerability* area. The bigger the area, the worse traffic disruption occurs in case of negative event.

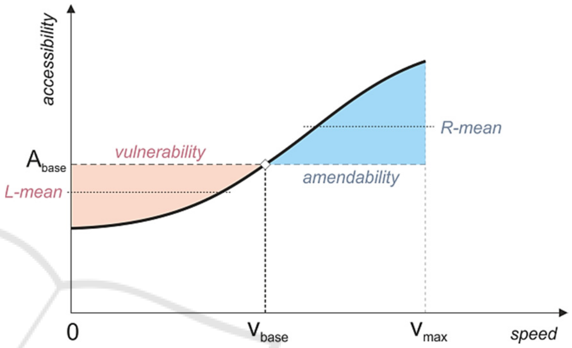

Figure 4: Profile functional structure.

The right part corresponds to improvements resulting in increased speed due to construction (e.g. surface or width improvement) or regulatory action (higher speed limit, vehicle-type restrictions). This is the *amendability* area. The bigger the are, the better results may be achieved. A base point is neutral and corresponds to current state of affairs. Please note, that this “attachment” point for the profile is actually not located in the middle, but on the right side for a good road or left side for poor road. Thus, low speed segments have small vulnerability area and cannot do much harm to the network in case of failure. High speed segments have small amendability area and cannot give much improvement (in many cases they have no amendability area at all).

Actual profiles given by series of simulations are not smooth. They are approximated by nine speed points, spread evenly across 0 – 130 km/h range. Extra tenth value comes from the base model itself and is computed once only. The test run results are illustrated on Figure 5.

Observations on the shape, inclination and attachment point give a complete information about road segment’s importance and it’s influence on the network. We may choose to observe the influence on whole system or on particular node. This is why two kinds of profiles will be computed:

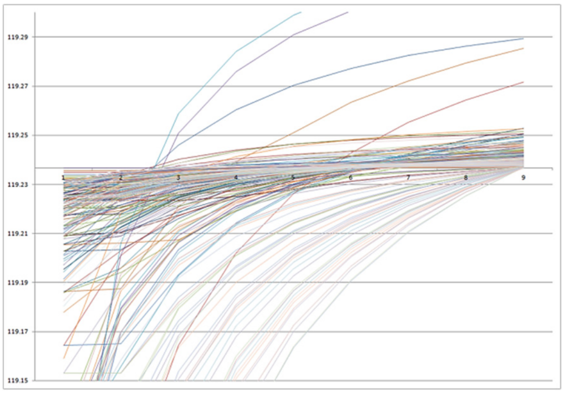

Figure 5: A sample of response profiles from test run.

- global profile with Y-axis describing the accessibility response of the whole system, and
- local profiles describing the accessibility responses of a single nodes.

4 OBJECTIVES AND EXPECTED OUTCOME

A series of descriptive and analytical procedures will cover following topics:

1. Assessment of magnitude of influence across segments (global accessibility).
2. Assessment of profile shapes and categorization.
3. Ranking of segments according to global influence, with mapping.
4. Mapping of global vulnerability and amendability (see Figure 6 and Figure 7 for preliminary maps).
5. Comparing global vulnerability and amendability, seeking and summarizing coincidences and differences.
6. Exploring the “foot” shaped profile phenomenon (see Figure 5), which suggests a redundancy of connectivity.
7. Comparing local accessibility magnitudes with global effects.
8. Observing the relation of high-impact segments to high-traffic segments. Challenging the thesis that these always coincide (evidence exists).
9. Observing and quantifying the distance between high-impact segment and it’s target node (the node being influenced), based on local accessibility. Supporting the thesis on far-reaching influence.

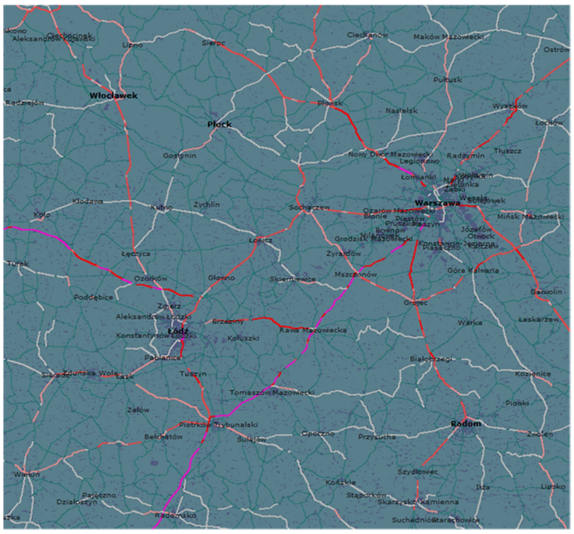

Figure 6: Vulnerability (L-mean) map of road segments.

4.1 Challenges

Data Volume

Major objective of the first phase of analysis is taming the sheer volume of data. Simulation of global accessibility response brings 14400 profiles. Simulations of local (node-related) accessibility brings another 2321× 14400 = over 33 million profiles. Each profile is composed of 10 values. An analysis should keep the profile data as a series and not a unordered set or independent dimensions. Time series analysis tools seem to be inappropriate because the length of a series is limited.

Synthetic Measures

Two kinds of measures are necessary: one capturing the magnitude of accessibility change, the other – the structure (shape) of the profile. So far, for testing and demonstration purposes, two simple magnitude measures were computed (see Figure 4): R-mean, a mean of amendability area under the right side of the profile and L-mean - a mean value of vulnerability area above left side of the profile. These are not capable of capturing the variability of the width of the profile and probably will be dropped in favour of integral-based (surface) measures.

Mapping

Very detailed structure of the network must be preserved to distinguish objects and this precludes varying line widths and use of symbols. Colour alone does not give good readability, especially for paper medium.

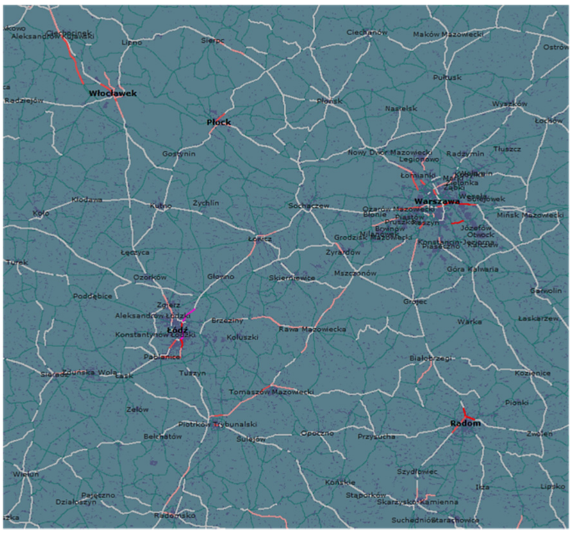

Figure 7: Amendability (R-mean) map of road segments.

5 STAGE OF THE RESEARCH

New software – OGAM Lab – has been developed to complement OGAM capabilities with massive simulation. Both programs share code responsible for core functionality (reading network data, model specification, shortest path algorithm etc.). Currently OGAM Lab performs two tasks, and these have been already completed for proper 2014 data:

- computation of path matrices (14400 files totalling 130GB of data)
- computation of accessibility cube: a data file with dimensions: nodes x edges x no. simulations = 2321 x 14400 x 10.

The architecture allows for seamless inclusion of next jobs, and these will be focused on accessibility cube analytics.

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APPENDIX

Total accessibility

Summary countrywide accessibility computed as a weighted total of node's values. The weighting occurs by node population P_j raw or fraction.

$$A_{total} = \sum_j A_j P_j, \tag{3}$$

Self potential

Self potential that is a measure of extra interaction occurring *within* a node. It is based on assumption that a great deal of transportation activity is released for very short trips, confined to immediate node vicinity. As this activity occurs below model resolution, it must be accounted for in special way. Compared to formula (2), an extended formula

$$A_i = D_i F(c_{ii}) + \sum_{j<>i} D_j F(c_{ij}) \tag{4}$$

includes the front term with c_{ii} – the mean internal cost (time) of travel within a node. This variable is provided externally and is based on administrative unit size.