On Accessibility and Energy Efficiency Modelling

INTRODUCTION

This paper concerns the issues of tools and methods for assessing employment (in)accessibility, an issue that affects sustainable development, and the impact of the measures sustaining accessibility on consumption of energy and consequent impact on global warming. The paper discusses theoretical background and computational algorithms of a GIS model that is being developed at the Czech University of Life Sciences, Prague. The model presented here has initially started as a design of a tool for analyses and assessment of the effects the proposed or existing spatial organization of territories has on accessibility of employment, namely exclusion of certain areas/social groups from the regional job market, when assessment of the efficiency of the whole system from the point of view of energy consumption is its initially unexpected extension.

Accessibility is a concept that is being used mainly in the field of social geography and is defined as "**an ability to be reached, entered, influenced**" (SOED, 5TH edition). The importance of accessibility for the socio-economic sustainability of local communities has been widely agreed in recent times (e.g., Smailes et al., 2002; Zenou and Smith, 1995; Milbourne, 2004). The main factor that impedes extensive use of accessibility in planning practice is disagreement in the socio-geographic society itself on the means of its description and explanation. Rural social geographers (Milboune, 2004; Shubin, 2006) tend to assess accessibility through detailed sociological surveys. This is a valuable approach inasmuch as it offers a deep insight into local opinion. However, these methods are rather impractical, due mainly to the uniqueness of the respondents' replies and/or the inaccuracy of the questionnaire method. Gathering data in this way is extremely difficult and costly.
Regional geographers on the other hand tend to replace true accessibility by density of population (Smailes, 2002) or by density of goods (Soares, 2001). Unlike social surveys, densities are quite cheap to acquire. However, they can give quite misleading results. Smailes (Smailes 2002), pointed out that the decisive factor seems to be **local settlement pattern** (i.e. spatial distribution of population, transport infrastructure and goods) rather than mere density figures. This indeed conforms to the to the daily experience of people (planners themselves included) who tend to value their environment by "how convenient is it to groceries shop" than by "how many groceries are there per square kilometer" (although these correlate usually).

There are two possible perspectives from which the issue of accessibility may be approached. The first is active (i.e. the perspective of an individual), which may be defined as *"the ability to reach, enter influence"*. The second being passive (the perspective of the "good"), i.e. *"the ability to be reached, entered"*. The authors' of this paper humble opinion is that the latter is better suitable for accessibility assessment for planning purposes. The argument here is that it is better grounded in theory of regional geography and related sciences (see Christaller, 1933; Gottmann, 1966 or Mc Arthur and Wilson, 1966) as well as its results suite better the needs of planning (identification of areas where from the "good" is effectively accessible). The reason that led the authors of this paper to select employment as the basic good derives from The Theory of Island Biogeography (Mc Arthur and Wilson, 1966) specifically from the schematic link recources (food) ~ employment, stated as: *"Accessible resources are those resources that can be effectively used by the members of a community. In the case of territorial species the available resource is usually a vacant territory. In the case of humans an accessible resource is a job vacancy (or a welfare system)."* .

When extending the model for assessment of the contribution to the global climate change we base our argumentation on the findings of 2007IPCC report (Solomon et al., 2007), which argue that CO2 emission may have an impact on global warming.

CONCEPT: ACCESSIBILITY

Let us assume that there is a single place where all the employment in an area is located. We assume that any job offer will have an attraction zone (i.e., it has an impact beyond the place itself). It has long been understood that the strength of a function declines as the utility of commuting decreases (Isard, 1956, cited in Levinson, 1998). This decline in attractiveness over a distance is referred here to as the "distance-decay factor". The attractiveness of an offer would decrease in concentric circles under the condition of isotropic transportation ease (this is still a very simple case indeed). Attractiveness is therefore a function of distance and initial attractiveness.

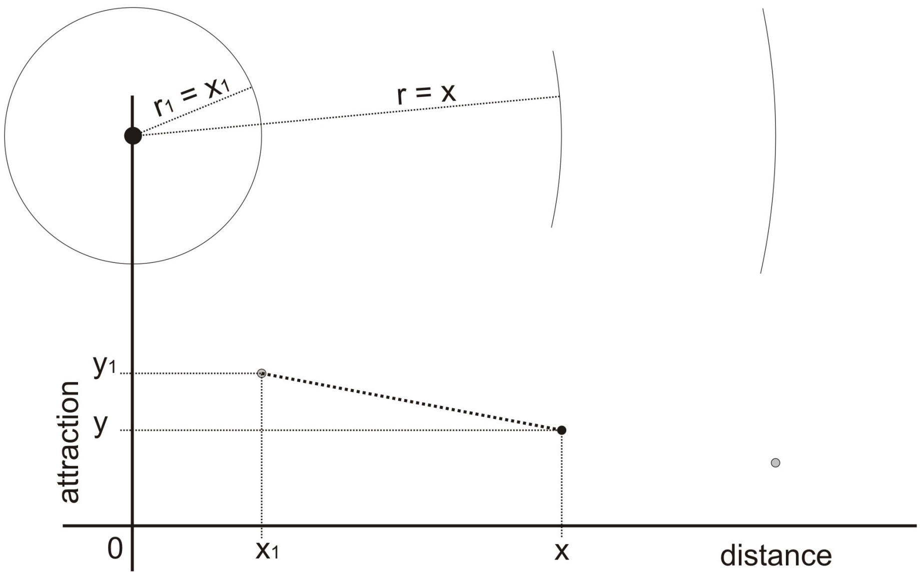

Figure 1: The concept of decreasing attractiveness with growing distance. Above: Plan view. Below: Decrease in attractiveness.

Initial Attractiveness

Let us first focus on the problem of the initial level of attractiveness. In all real life situations there are two factors that may affect the impact of a job offer in a central place on more or less distant places. The first factor is the number of job offers, which expresses its relative importance for sustaining the material existence of the population both in itself and its surroundings (De Jong & Ritsema van Eck, 1996; Levinson, 1998). As such, it is a functional analogy of the size of an island in the Theory of Island Biogeography, thus:

$$a = \Sigma \text{Jobs} \tag{1}$$

This would work perfectly if the local inhabitants (the lucky ones that happen to live directly in the central place where the job offers have been created) did not have the advantage of proximity. Outsiders are disadvantaged by the additional cost of commuting (just as in ecology), not to mention the lack of information on new job postings. For this reason, some authors (e.g. Wee et al., 2001) suggest incorporating a second factor alongside attractiveness, which is competition. Wee et al. suggest this in the form:

$$CF = \Sigma Jobs / \Sigma emp \tag{2}$$

where "ΣJobs" stands for employment opportunities (active jobs located in the node), "Σemp" stands for competitors. As was mentioned above, both the jobs offered and the job seekers on the market are assumed to be perfectly substitutable. All "applicants" are assumed to be job seekers. Including the competition component into the formula (1) for the economic aspect of the attractiveness value of the central place leads to the following form:

$$a_{0E} = \Sigma Jobs \,.\, \Sigma Jobs / \Sigma emp = (\Sigma Jobs)^2 / \Sigma emp \tag{3}$$

It is beneficial to use the competition-adjusted value of the economic attractiveness of the central place, since it takes into account the orientation of the central place's employment market; a passive employment balance (more applicants than job positions) adds to the obstructions that commuters seeking employment have to face anyway.

The Distance Decay Factor

Having stated that the attractiveness of a central place for an individual decreases with rising physical distance, it is necessary to quantify this decrease. Many authors claim that it is not the physical distance itself that influences the subject's motivation to commute. The true factors that affect an individual's tolerance to commuting length should be commuting time (e.g., Tse et al., 2003; Schwanen & Dijst, 2002; Wee et al., 2001; Van Ommeren et al., 1999) and commuting costs (e.g., Zenou & Smith, 1995; Rouwendal, 1999). Physical distance is therefore only a second-order determinant, the use of which is reasoned by the spatial imprint of the effects of commuting patterns (Kwan & Weber, 2007; Shen, 1998, Cervero, 1996). Commuting distance-decay functions should represent individual rational decisions on the utility of commuting.

The commuting cost (dis)utility function is based on the rational assumption that individuals will commute only when the excess income is greater than the costs of commuting, thus:

$$C_C = f(\Delta I) = f(I_D - I_L + \Delta R) \tag{4}$$

where "C_C" is the commuting cost, "ΔI" stands for the difference in income, "I_D" and "I_L" distant and local income respectively, and "ΔR" is the difference in residential costs (mortgage, rent). Commuting cost capability is expected to correlate positively with differences in income level, which has been both modeled (Kulkarni, 2000; Zenou and Smith, 1994) and empirically proved (Nutley, 2003; Green & Meyer, 1997; Pazy et al. 1996).
Practical use of the commuting cost factor for distance decay function analysis is complicated by the fact that most of the required data is difficult to acquire: both income levels and true residential costs are protected personal data. In addition, property values do not follow the commuting cost patterns, as other factors are co-involved in the location decisions of the better-off, as has been proved in many case studies (e.g., Tse & Chan, 2003). This difficulty can be obviated by assuming the income levels (as in Kulkarni, 2000, Zenou and Smith, 1996) and neglecting (or assuming) the residential costs. However, the complications connected with commuting cost input data are so great that they effectively make it impossible to use commuting costs as an explanatory factor for the commuting patterns in the environment of the Czech Republic. This does not, of course, diminish the importance of commuting costs. Some studies have shown that direct commuting costs

effectively exclude certain social groups from the job market (Kulkarni, 2000; Zenou & Smith 1996; Milbourne, 2004; Smailes, 1997; Cloke et al., 1995).

The commuting time utility function seems to have slightly less exact grounds than does the commuting cost utility function. The commuting time utility function is based on the assumption that any individual is willing to invest just a portion of his/her free time in daily commuting. Even if the direct commuting costs are assumed to be zero, the discomfort of having to spent time on commuting repels people from commuting. The acceptable commuting time function can be written as follows:

$$C_T = f(t_c; \alpha) \quad (5)$$

Where "C_T" stands for time distance decay factor, "t_c" is one-way commuting time, and "α" is an individual commuting resistance factor. The *commuting resistance factor* expresses the individual's willingness to invest time in daily commuting, e.g. the longest commuting time he or she will tolerate. This tolerance is highly individual, and mainly depends on the individual's family status, on the specific job offer, and on the means of transportation. Absence of children and a good-quality job seem to raise the commuting time tolerance (Pazy, 1996; Sermons, 2001). Commuting time is rather easy to compute, the form suggested by Victor Lorenz (Lorenz, 1961) being:

$$t_c = t_w + \tfrac{1}{2}\,\mathrm{int} + t_d + t_{w2} \quad (6)$$

where "t_w" and "t_{w2}" are times for walking from residence to bus stop and from bus stop to workplace, "½ int" stands for half the interval between buses, and "t_d" is the time of the bus journey.

There have been many attempts to quantify the shape of the curve of the distance decay function, based on geographical distance, time or cost. The resemblance of the concept of attraction to the concept of gravitation led to the development of the so-called "gravity model" as early as the end of the 19th century (Ravenstein, 1885, cited in Wilson, 1981). This model was developed for assessing the traffic between two centers, and it works quite accurately over a certain distance interval. However, for more accurate studies it presents several severe problems. Firstly, there is no reason to expect the attractiveness to decline at the square of the distance (Thomas & Huggett, 1980, cited in Sklar & Constanza, 1991), no central place can surely exert infinite attractiveness, and last but not least the interaction between two centers is hardly ever symmetrical. As the distance-decay function derived from theoretical physics has the above mentioned limitations there were multiple alternative solutions on the same basis. From among these, the negative exponential function proved to be the preferred form for describing the distance-decay of the attractiveness of a center. The negative exponential function has three pleasing characteristics: unlike the original gravity equation it reaches definite values at zero distance from the place of attraction (central place), it decreases relatively rapidly close to the place, and slows down with increasing distance, which more or less conforms to the experience of human behavior (Levinson, 1998), and it never reaches a zero level, which conforms to the Central Place Theory (Beavon, 1977). The shape of the negative exponential function even conforms to the geometrical Van Thünen landscape models (Paynter, 1982; Hoover, 1975). The decrease close to the central place itself is, however, somewhat too rapid to conform to observed human behavior.

Once we accept that people are just a (special) animal species, there is no reason to expect an analysis of large samples of human individuals to show anything other than some normal probability distribution with a mean, median and standard deviation in the case of resistance to commuting (rather than a negative exponential). The shape of the attractiveness distance decay would change from the Δ shape of a negative exponential function to the Ω shape of a cumulative probability function.

The omega shape seems to be more appropriate than the exponential function for describing distance decay, because the decay is very small at the beginning of the curve (short travel time from the central place) and then drops rather rapidly to a level that is again nearly stable. (Compare the shape of experimental commuting time tolerance with the shape of a theoretical probability distribution function, see figure 4).

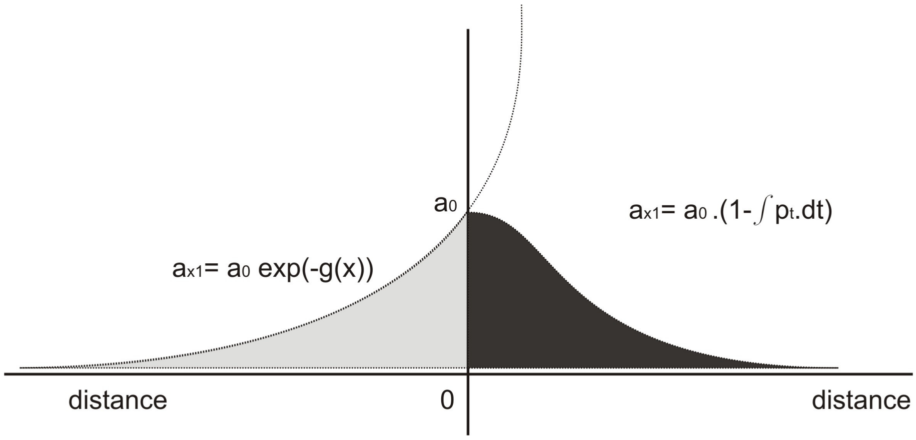

Figure 4: Illustration of the difference in shapes of the exponential and probability distributions of the distance-decay factor

The normal probability distribution seems to be more appropriate for describing the distance decay factor of “a general” human population. The form of the distance decay function will then be:

$$Att = Att_0 * \Psi(t) = Att_0 * \exp\{i.\mu.t - 1/2\sigma^2 t^2\} \quad (7)$$

where “Att” is the distance-decayed attractiveness of a central place, “Att_0” is the level of attractiveness at the place itself, “μ” is the median of the normal distribution, “σ” is its standard deviation, and “t” is the commuting time. The “σ” and “μ” parameters define the shape of the function, and therefore bear information about the “laziness” of the subject population. Introducing the probability distribution of subjects’ will to commute for a certain time adds a qualitative value to the accessibility results.

Attractiveness vs. Accessibility

It is easy to quantify decay of attractiveness of a single central place that offers employment. It is enough to “shrink” the space around it to the distance of the decisive factors (whether it is a time or a cost). Then a proper function of the distance decay expresses the loss of attractiveness of the place from outside.

When there is a polycentric system, the situation becomes slightly more difficult. The attraction zones of individual central places can overlay and therefore add to the overall accessibility of resources. Let us assume that we have an exponential distance-decay factor function and two equal central places. Accessibility concerns an individual's access to opportunities located at one of the given central places. Maćkiewicz and Ratajczak (Maćkiewicz & Ratajczak, 1994) therefore suggest summing the attractiveness values of the distinct attraction zones present at the surveyed point. For the given point $a_{d/2}$ from figure 5, we therefore have two distinct levels of attractiveness and one level of accessibility.

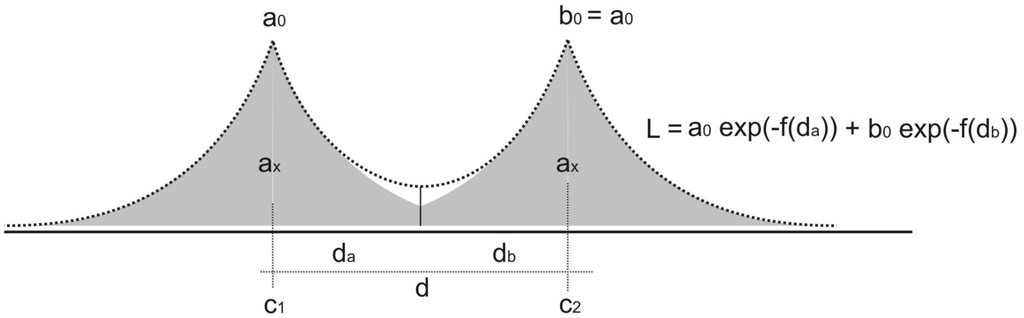

Figure 5: Illustration of a double nodal situation, distinguishing between attractiveness (grey surface) and accessibility (dotted line) levels.

Acc(x,y) = Atta(x,y)+ Attb(x,y) (8)

This principle generally applies for literally any number of central places whose attraction zones overlap at a point in a space, so that:

Acc(x,y) = $\sum$Att $(x,y)_I$ (9)

The accessibility/attractiveness dichotomy, and its effects on model accessibility patterns, conform both to the theory of island biogeography and to the hypotheses of human geography presented above. If applied as an independent tool for explaining the concepts of these theories, the presented theoretical approach gives similar results.

CONCEPT: ENERGY EFFICIENCY OF TRANSPORTATION SYSTEM

The concept of efficiency of the transportation system from the perspective of COx emissions is relatively simple. Efficiency of transportation system is assessed in compound daily CO2 emission per user of the system (including cyclists and pedestrians). Any means of transportation has specific COx emission per kilometer distance. The model counts with the following values of COx emissions. Pedestrian and bicycle are assumed to have no excess COx emissions. Unit emissions of passenger cars are assumed to conform on average to the EC regulation No. 443/2009 – i.e. 130 g/km. Unit emissions of busses is assumed to conform to the expectation of the Japanese Ministry of Land, Infrastructure and Transport (Wani, 2007), i.e. 416 g/km. The Japanese values have been used for the EU uses gCO2/kwh (EC regulation No. 55/2007).

The overall daily emission from public transport operation is simply sum of daily cruised kilometres multiplied by the bus's emissions of COx, i.e.:

Ept = x . l . Eb (10)

where "Ept" stands for overall daily emissions in grams of COx, "x" is number of lines per day, "l" total length of the bus lines in kilometers and "Eb" are unit emissions in g/km.

The COx emissions that originate from passenger cars is computed from the following equation>

$$Epc = 2 . l . Ec \qquad (11)$$

Where "Epc" stands for one day travel emissions, "l" stands for the distance from place of the residence to the employment centre, which needs to be doubled for there are two trips (there and back) expected, "Ec" stands for unit emissions.

The crucial step in the analyses is the assessment of the share of people in the region using the different means of transportation. Each spatial unit within the system has a specific accessibility levels for different modes of transportation. The model assumes that the working population would use the least costly means of transportation as long at the commuting time is acceptable. In a settlement unit of 200 working inhabitants where for 80% of people would travel by car, 60% would travel by public transport, 20% would cycle and 0% walk (see eqs. 8:10) the final equation for per capita COx emissions ooks as follows:

$$Et = (0 + 0/40 + \Sigma\ x . l . Eb/80 + \Sigma\ 2 . l. Ec/ 40)/ 180 \qquad (12)$$

The result for the spatial unit than reflects not the realized (for it does not attempt to resolve the preference model of the commuters) but the least expectable emissions of COx.

THE MODEL COMPUTATION SCHEME

Application of the concept presented here makes use of standard GIS analyses. The structure of the model is as follows.
The accessibility framework is created by a network of means of public transportation. Time spent using public transport can be treated in two ways. The more elegant way is to use ESRI Network Analyst, where each line of public transport is a distinct feature of the network attributed with time distance between individual stops. Using the standard ESRI Spatial Analyst is somewhat less elegant. The physical structures of each means of transport (trains, buses etc.) are features attributed with the speed of motion of the means of transport (average bus velocity).
In ESRI Spatial Analyst, the time consumption for the means of transport is therefore computed from the physical distance, while in ESRI Network Analyst time is a direct attribute of the connection (there is no computation in between).
The stops are treated as nodes on the polylines of the respective features, either direct connections (network analyst) or representations of the physical structures (spatial analyst). Each stop is attributed a time penalty for taking on and setting down passengers and/or a time penalty for changing the means of transport).

Each employment central place has only certain stops in the transportation network attributed to it, where the attractiveness is full. The attractiveness of each central place in the system is automatically computed from the database attributed to the feature type "stop", in accordance with equation (3) in this paper. Numbers of job positions and the economically active population need to be added manually to the database.

The final stage - accessibility of places within the analyzed area - is made as the following three step vector analysis. First two steps calculate attractiveness of each employment central place of the system over the territory and the third step recalculates the attractiveness into overall employment accessibility
First, mere time-travel distances are computed separately from each centre of employment to all of the stops of the transportation system. This is done by a travel time matrix, either automatically from the connections ESRI Network Analyst or by calculation of travel times in ESRI Spatial Analyst. Walking distances from the stops on the transportation system are

created as buffers around the stops. Each travel time distance is therefore computed according to the equation (6) of this paper.

The second step is to recalculate "time" to "attractiveness". The result of the time-travel distance analysis is recalculated using equation (7). The output of the first step is then a set of GIS vector shapes that represent the level of attractiveness of each employment central place over the territory.
In the third step, as accessibility according to equation (9) of this paper simply sums up the individual levels of attractiveness, the shapes of attractivity break up into fragments and sum the corresponding attractivity levels. This results in the overall accessibility of each square of the fragments. This is what we had set out to assess.

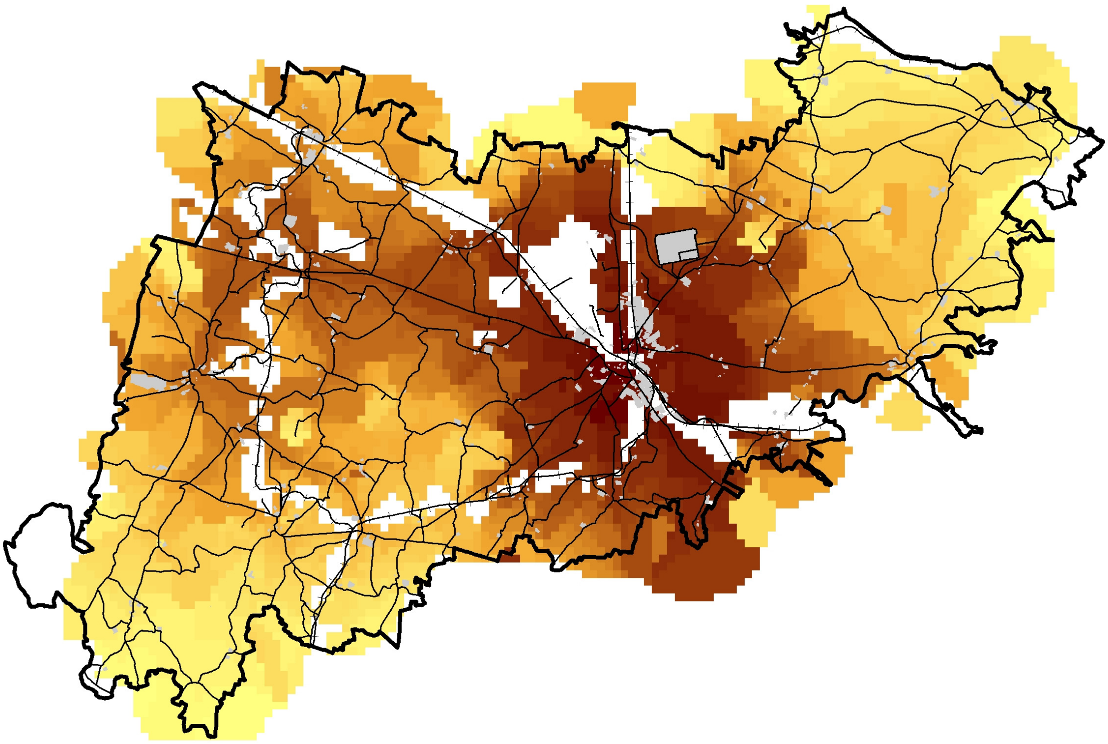

Figure 6: The model output -accessibility represented by COx emissions required to sustain the level of accessibility. Darker colour indicates better (less COx intensive) accessibility.

The forth and last step of the model each of the squares is recomputed according to the eq. (12) of this paper which results in a map as in figure 6.

CONCLUSIONS

The proposed method for calculating functional accessibility (or remoteness) is not a thoroughly new idea. It attempts to integrate the results of numerous earlier research-based studies into a comprehensive system. It was designed to add flesh to the bones of theories already in existence.
The model attempts to provide the planner with a map that indicates the energy efficiency of the labour/ employment/ transportation system proposed in a regional plan. It is therefore being designed so as to be easily adjustable for effective scenario building (i.e. to be relatively data extensive, and reasonably automated). The model algorithms are based on analyses of public datasets in the Czech Republic. Further research is necessary especially concerning the (dis)utility of the different means of transport that will allow better assessment

of the means-specific accessibility levels. This will require sound sociological survey which in-so-far exceeded the capacity of the authors of this paper.

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