Mathematical model of assessing urban planning decisions based on capital construction facilities location under the city plan

A V Zedgenizov¹, A I Solodkiy² and K V Seliangin³

¹³ The Department of Oil and Gas Engineering, Irkutsk National Research Technical University, 83 Lermontov street, Irkutsk, 664074, Russia
²The Department of Transport Systems, Saint Petersburg State University of Architecture and Civil Engineering, 4 Vtoraya Krasnoarmeiskaya Street, Saint Petersburg, 190005, Russia

E-mail: azedgen@gmail.com

Abstract. The article deals with the issues of placing large focal points over the city planning map. The topicality of this issue is described. The target function is determined; it takes into account the time losses of road users in the zone of the focal point influence and the amount of payments to budgets of different levels generated by the focal point functioning. The mathematical model that allows estimating time losses of road users is presented. The model has a special focus on the mechanism of transport demand development and on the assessment of crossing capacity based on the intensity of priority flows. The mathematical tools are developed; they allow calculating the financial consequences of the implementation of urban planning projects set out in the city plan, choosing focal points with the most beneficial influence on the municipal budget among the proposed ones, taking into account the minimum negative impact of the chosen focal points on the adjacent street-and-road network. Some particular cases of the transport demand development are discussed, for example, those of traffic management schemes that do not allow left-turn and through movements at uncontrolled intersections. The recommendations on the practical application of the target function when making urban transport decisions having regional and city significance are developed.

1. Introduction
Modern cities are a conglomerate of focal points (FPs) located, as a rule, in capital construction facilities (CCF) that can be different in the following characteristics: the number of floors, area, configuration, remoteness from the city center and transport communications [5, 12]. Depending on the intended use, type of ownership, degree of the target audience coverage, investment prospects, availability of engineering, transport and social infrastructure, as well as on a number of other factors, designers determine the specific location of capital construction facilities over the city map. The amount of correspondences (transport demand) made to FP will largely depend on the choice of its location. For example, if FPs are non-profit and the state authorities or public organizations define their locations unreasonably it leads to increased time losses of potential users and may create an additional load of the street-and-road network (SRN) providing these FPs functioning. When it comes to commercial organizations, transport demand is a direct factor affecting the number of visitors to such FPs and, consequently, the revenues, i.e. the commercial gains from these FPs functioning. FPs represented by
grocery stores (supermarkets) can serve as a good case of the location effect on the level of transport demand [2, 3]. Depending on its distance from the city center, i.e. proximity to apartment buildings (food is easier to buy after a work-to-home trip), the demand will increase. The demand will also depend on the distance from the public transport stop, the commuter train station or the subway: the closer the supermarket is to the stopping point, the higher the demand is. When it comes to the location in the direction of travel, the right-hand location usually provides quick easy access, therefore, the demand will be higher, while the left-hand location makes a potential visitor using public transport (PT) cross the roadway and a potential user in individual transport (IT) must make the left turn across the oncoming traffic flow.

In some cases, to increase the traffic capacity of individual sections of SRN, left turns are prohibited and, therefore, it requires significant excess mileage leading to the loss of such FPs’ attractiveness for potential visitors. On the other hand, the location of FP of the CCF type, especially a large one with the area of several tens of thousands of square meters (shopping malls and entertainment centres, residential neighborhoods, sports and competition grounds, etc.) can significantly affect the functioning of the adjacent SRN as such FPs are of high attractiveness including the episodic nature of such attractiveness. Therefore, the assessment of reasonable placement of capital construction facilities included in the city plan is the most important step at various stages of urban planning and transport design from the city’s general plan to traffic management projects.

2. Materials and methods

To identify the optimal location of CCF maintaining high transport demand and having minimal impact on the adjacent SRN [1,7,6], it is necessary to apply such a mathematical model that could take into account all the above-mentioned factors and the value of socially useful benefit would be considered as a resultant involving the time loss while passing the SRN section compared with the time loss absence (the basic version); besides, if this FP is a commercial one the resultant must be sensitive to the amount of taxes associated with this FP functioning. It should be noted that the time losses while passing the SRN section close to the place of the FP location should not exceed a certain reasonable limit, for example, the limit described as the service levels D or E in the special scientific literature [11]. In other words, even with the high financial significance of this FP location traffic conditions in the zone of its influence should not be appalling. Otherwise, the location of this FP should be reconsidered or some necessary changes in SRN should be introduced to reduce time losses in the zone of this FP location.

At this stage, it is worth applying the general mathematical formulation of the target function in a certain region of finite dimensional vector space limited by a set of linear and/or nonlinear equalities, as it allows finding the extremum in the discussed problem, i.e. optimal conditions within the limits of existing restrictions. The research process aim is to minimize the unit costs of FP functioning; the costs include the time of movement in the FP zone converted into the monetary equivalent (rubles) and the amount of tax payments:

$$3 = \frac{1}{T} \sum_{i=1}^{n} 3 \rightarrow min$$

(1)

where $3$ – unit costs for the definite time period, rubles; $T$ – estimated time, year; $3_n$ – time losses for movement, rubles; $3_n$ – costs for paying taxes to budgets of different levels induced by FP functioning, rubles.

3. Results

If it concerns uncontrolled intersections providing the definite FP functioning the traffic management scheme should be explored in order to take into account the left and right turns, the number of lanes on approach zones including additional lanes for turning maneuvers at such intersections. The transport delay should be calculated according to the following dependence [16]:

$$d = \frac{3600}{C_{res}}$$

(2)
where $d$ – an average transport delay at the intersection on the minor road, s/car; $C_{res}$ – reserve capacity of the traffic flow on the minor road is calculated according to the formula:

$$C_{res} = C - N$$

where $C$ – reserve capacity of the given traffic flow at the uncontrolled intersection, car/h; it is calculated on the basis of geometry rules, number of lanes, traffic management scheme, intensity of the priority traffic flows and other factors; the intensity of the minor road flows providing, as a rule, the FP functioning should be regarded as the transport demand of visitors using IT [4].

$$N = E_{sum} \cdot \frac{d_{um}}{P_{um}} \cdot k_{v}^{d} \cdot k_{d}$$

$$C = \left( 3600 \cdot e^{-\frac{q_{p}}{3600}(t_{r} - t_{f})} \right) \cdot \left( \prod_{j=1}^{m} 1 - \frac{N_{0j,j}}{c_{0j,j}} \right) \cdot \left( \prod_{j=1}^{m} 1 - \frac{N_{0j,j}}{c_{0j,j}} \right)$$

where $E_{sum} –$ transport demand, persons/day; $d_{um} –$ ratio of people using IT during the definite hour; $P_{um} –$ average number of people in a vehicle (IT), persons; $q_{p} –$ intensity of the 1st rank traffic flow intersecting the studied traffic direction, car/h; $k_{d} –$ coefficient involving the ratio of the traffic flow distributed between the intersections of the given FP (if there is one intersection, $k_{d} = 1$); $k_{v}^{d} –$ coefficient of daily irregularity of departures; $n –$ number of traffic flows in the movement direction; $tg –$ average marginal interval, s; $t_{f} –$ average following distance, s; $N_{0j} –$ intensity of the 2nd rank traffic flow intersecting the studied traffic direction, car/h (if there is not any, it is eliminated); $N_{0j} \cdot k_{d} –$ intensity of the 3rd rank traffic flow intersecting the studied traffic direction, car/h (if there is not any, it is eliminated); $c_{0j} –$ traffic capacity of the 2nd and 3rd traffic flows intersecting the studied traffic direction, car/h (if there is not any, it is eliminated); $m –$ number of the 2nd and 3rd traffic flows intersecting the studied traffic direction.

$$d = \frac{3600}{\left( 3600 \cdot e^{-\frac{q_{p}}{3600}(t_{r} - t_{f})} \right) \cdot \left( \prod_{j=1}^{m} 1 - \frac{N_{0j,j}}{c_{0j,j}} \right) \cdot \left( \prod_{j=1}^{m} 1 - \frac{N_{0j,j}}{c_{0j,j}} \right) - \left( E_{sum} \cdot \frac{d_{um}}{P_{um}} \cdot k_{v}^{d} \cdot k_{d} \right)}$$

Given that the time spent on travelling should be converted and expressed in rubles, it is advisable to agree that the cost of delay $C$, when passing the studied section of SRN is 426 rubles/hour [9] for each IT passenger. Therefore, $3_{n} = d \cdot C_{n}$.

The amount of tax payments induced by the functioning of a commercial FP is determined under the current tax legislation and the list of taxes may vary depending on the FP type: canteens, cafes, bars, restaurants, production shops, shopping malls, administrative and office buildings, i.e. all those CCFs that are legally registered as non-residential and are used for gaining revenues. The owner calculates and makes payments under the tax laws. Terms of payments are set by regional authorities.

Thus, the final target function will look as follows:

$$3 \cdot \left( \left( \frac{3600}{t_{f}} e^{(-t_{r} - t_{f})} \right) \cdot \left( \prod_{j=1}^{m} 1 - \frac{N_{0j,j}}{c_{0j,j}} \right) \cdot \left( \prod_{j=1}^{m} 1 - \frac{N_{0j,j}}{c_{0j,j}} \right) - \left( E_{sum} \cdot \frac{d_{um}}{P_{um}} \cdot k_{v}^{d} \cdot k_{d} \right) \right) \rightarrow min$$

4. Conclusion

The developed tools are necessary for making reasonable urban and transport planning decisions aimed at identifying the maximum benefit to the State treasury when choosing the type of FP. In other
words, it is possible to calculate the financial consequences of the implementation of urban development projects set out in the city plan, to find out which FP (CCF) among the proposed ones can have the most beneficial effect on the municipal budget and the minimum negative impact on the adjacent SRN.

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