Impact of Transport Zone Number in Simulation Models on Cost-Benefit Analysis Results in Transport Investments

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Abstract. Nowadays, feasibility studies need to be prepared for all planned transport investments, mainly those co-financed with UE grants. One of the fundamental aspect of feasibility study is the economic justification of an investment, evaluated in an area of so called cost-benefit analysis (CBA). The main goal of CBA calculation is to prove that a transport investment is really important for the society and should be implemented as economically efficient one. It can be said that the number of hours (PH – passengers hours) in trips and travelled kilometres (PK – passengers kilometres) are the most important for CBA results. The differences between PH and PK calculated for particular investment scenarios are the base for benefits calculation. Typically, transport simulation models are the best source for such data. Transport simulation models are one of the most powerful tools for transport network planning. They make it possible to evaluate forecast traffic volume and passenger flows in a public transport system for defined scenarios of transport and area development. There are many different transport models. Their construction is often similar, and they mainly differ in the level of their accuracy. Even models for the same area may differ in this matter. Typically, such differences come from the accuracy of supply side representation: road and public transport network representation. In many cases only main roads and a public transport network are represented, while local and service roads are eliminated as a way of reality simplification. This also enables a faster and more effective calculation process. On the other hand, the description of demand part of these models based on transport zones is often stable. Difficulties with data collection, mainly data on land use, resulted in the lack of changes in the analysed land division into so called transport zones. In this paper the author presents an influence of land division on the results of traffic analyses, and hence on CBA outcome. Moreover, the paper shows that the effectiveness of investments as represented in the results of cost-benefit analyses is strictly correlated to a transport model detail.

1. Introduction

Most transport investment projects that are being implemented in Poland at present are co-financed with the European Union funds within domestic and regional competitions. The long list of negligence in the transport infrastructure development before Poland joined the European Union, including with regard to roads, tram systems and railway network, has made the co-financing of such investments one of the priorities in EU funding. As a result, most towns, cities, and regions are developing study and design documentation concerning such investments. The scope of projects is highly diversified. Some of the investments result from transport studies as necessary for the proper development of an area. There are other investments, which do not stem from development plans and assumptions, but only from the
potential to finance them. Differences in the quality of investment preparation arise not only from the quality of design documentation, but also from the justification of project implementation. The reliability of economic studies conducted within the so-called cost-benefit analysis (CBA), which justifies a purpose of an investment project, results to a large extent from the correct assumptions concerning transport supply and demand. Simulation transport models, which constitute an essential tool required by the European Commission to analyse transport demand and supply in an area, are developed with very different detail levels. Such a detail level stems in most cases from the size of area to be analysed. In the present domestic traffic model, only national and provincial (voivodeship) roads have been described, while in most provincial models the scope of the supply side of the description has been extended with local roads, and in city models with major municipality roads. An additional element that affects the level of analysis accuracy is the division of analysis area into trip origins and destinations, so-called transport zones. State the objectives of the work and provide an adequate background, avoiding a detailed literature survey or a summary of the results.

In this article, a city with the population of 350 thousand is used as an example of creating an analysis of the influence of dividing a modelled area into transport zones on the traffic modelling results, and thus the data that constitutes the foundation for CBA of transport projects.

2. Idea of transport models
Transport models, which are also referred to as traffic models, were constructed as early as in the 1950s. One of the first such models were used to plan the development of the network of highways in the United States. Since then, transport models have undergone a number of changes, aimed primarily at improving the reliability of analysis results.

The purpose of transport models is to describe transport phenomena that occur in the analysed area with mathematic formula, which enable to recreate trips of residents during a specified period. Transport models generally concern rush hours, but also full day periods, usually on working days and during periods of intense tourist traffic, if any. The correct mathematic description of transport processes makes it possible to carry out a number of analyses that concern the effects of changing a transport infrastructure, for example the effects of building a new road. By calculating the value of traffic volume to be expected in a new road section, one can successfully estimate the parameters necessary to design the section. If a model operation can be extended to forecast periods, such analyses become an indispensable element in planning transport infrastructure development, which is like a blood circulation system for areas of human activity. Therefore, the problems of building and applying transport models are attracting more and more attention, often becoming a task of the national or international importance.

In general, the supply and demand sides are distinguished in transport models. The supply side includes transport infrastructure: roads, crossroads, tram lines, railway lines, underground, stops, and stations as well as the description of the public transport system operation, including routes of the means of transport, numbers and frequencies of runs within public transport, means of transport, etc. The scope of the supply description is usually limited to the most important transport routes and the whole public transport system. The demand side stems from transport needs of residents, when differences between the place of residence and the location of activities make residents move. The origins and destinations of trips depend primarily on the area (land use) development in the analysed zone, including in particular the homes of residents and locations of reasons for their trips, such as employment, education, shopping, or relaxation. The supply part describes the transport infrastructure, while the demand side concerns area development. In practice, an area is divided into smaller fragments, so-called transport zones, between which trips are to be taken by local residents in a given time frame. In a classical approach, the division into transport zones results both from the size of an analysed area and the potential availability of reliable data within area development and the computing capacities, including the speed of computing and software limitations. The most popular application dedicated to building transport models has been created by PTV Group Karlsruhe [1], Germany, a leader of IT solutions in planning and simulation in transport. In this application, the cost of purchase and a licence (including technical support) depends on the number of transport zones. Hence, like in the description of supply, where the limitation of
analyses to the transport network is a classic example of simplifying reality, in the case of demand the simplification is the generalization of trip origins and destinations. In practice, trips are taken not between zones but between buildings, and the local transport network, including access roads, is the common element of most trips. Moreover, there are no guidelines, standards, or requirements are regards the descriptions, either of the supply and demand sides. Examples of statistical data of selected transport models in Poland have been presented in Table 1. The values of traffic volume and passenger protocols are obtained as a result of simulating the selection of the probable routes of travellers within journeys between an origin and destination with a single means of transport (usually a trip by a private car or public transport). As a consequence of attributing the number of vehicles and passengers to individual sections of the road transport network and public means of transport in the period of analysis, data is generated on the total number of traffic volume and streams, as presented in Figure 1. Despite the above-mentioned simplifications in the definition of both the supply and the demand sides, all the transport models indicated in Table 1 have shown the compliance of results between simulations and reality. It means that traffic volume, and in selected examples also the values of passenger streams, measured at control points of the transport network, conform to the values of traffic obtained in computer simulations. Moreover, each of them can be applied successfully for simulation analyses necessary to prepare basic input data for CBA of transport investments.

Table 1. Characteristics of selected transport models in Poland.

| Modelling area          | Total area [km²] | Population [thousands] | Total number of zones | Number of internal zones a |
|------------------------|------------------|------------------------|-----------------------|---------------------------|
| National Traffic Model | 312 679.0        | 38 455                 | 485                   | 106                       |
| Bydgoszcz              | 176.0            | 355.0                  | 570                   | 553                       |
| Elbląg                 | 79.8             | 121.2                  | 68                    | 54                        |
| Legnica                | 56.3             | 100.8                  | 289                   | 275                       |
| Łódź                   | 293.3            | 698.7                  | 214                   | 189                       |
| Gdańsk                 | 262.0            | 463.0                  | 220                   | 190                       |
| Gdynia                 | 135.1            | 247.3                  | 194                   | 177                       |
| Płock                  | 88.1             | 121.5                  | 140                   | 100                       |
| Poznań (Poznań Agglomeration) | 261.9 | 541.6                  | 586                   | 369                       |
| Rybnik                 | 148.4            | 139.5                  | 68                    | 57                        |
| Krakow (Krakow Agglomeration) | 326.9 | 762.5                  | 423                   | 363                       |
| Szczecin               | 300.6            | 405.4                  | 410                   | 255                       |
| Tczew                  | 22.3             | 60.0                   | 107                   | 97                        |
| Toruń                  | 115.7            | 202.6                  | 601                   | 582                       |
| Warsaw(Warsaw Agglomeration) | 517.2 | 1748.9                 | 970                   | 801                       |

a internal zones — zones located within the limits of the analysed area, representing origins of internal trips and trips generated by the area of the analysis, other than origins of absorbed and transit traffic across the analysed area (external zones).

According to JASPERS Guidelines (Joint Assistance to Support Projects In European Regions) presented in the Blue Book [3] and in [4], data concerning vehicle-km and vehicle-h is the basis for the cost and benefit analysis. Differences obtained in the vehicle-km and vehicle-h results in individual transport investment implementation scenarios make it possible to estimate costs, e.g. of working time, costs of fuel, emissions of toxic compounds, road accidents, etc. Although one minute saved in the travel time for a resident of the analysed area seems to be negligibly small, when multiplied by the number of users, days in a year, and years of the investment efficiency analysis, it provides hundred thousands of hours saved. Does the accuracy of constructing a model applied in analyses contribute significantly to the above-mentioned differences in the estimation of parameters essential for economic analyses? Can a transport model that is more accurate, where the number of transport zones have been increased significantly, show greater savings in travel time for the analysed scenarios of transport infrastructure
development, thus proving the higher economic efficiency? Are actual economic effects of investments greater than those resulting from model computing?

![Figure 1](image_url)

**Figure 1.** A fragment of a map generated in the transport model of the city of Warsaw with marked total volumes of individual traffic (IT) and streams of passenger public transport (PT) [2]

3. **Research hypothesis**
Transport models, where origins and destinations of trips are defined accurately owing to their greater density, reflect more reliably transport processes, thus enabling the more precise determination of economic effects of transport investments. If internal traffic without transport zones is omitted, the transport work in transport networks becomes significantly underestimated, which affects the results of cost and benefit analysis of transport investments.

4. **Testing grounds**
In the first stage of the study, a transport model of Bydgoszcz was used, prepared for the transport study of that city. The selection of the testing ground resulted both from the fact that the author of the analysis was a co-author of the model and from the availability of large volumes of detailed data that describes both the transport infrastructure of the city and its area development.

Bydgoszcz is a medium-sized city, the eighth largest in Poland, of the area of almost 176 km², with population of approximately 355 thousand, which gives the population density at 2,017.2 person/km². The city features numerous green areas and its shape is latitudinal (see Figure 2). Both the northern and southern parts of the city are green areas, mostly forests. The basic transport network stretches from the east to the west for about 25 km and from the north to the south for about 6.5 km.

The transport model of Bydgoszcz was developed for the transport study of the city in VISUM in 2012, where the area development directions and the transport infrastructure were defined in the forecast until 2050. The supply part of the model was defined based on the records of transport routes according to the OpenStreets portal and the direct stocktaking conducted during field visits. The supply side
comprised road infrastructure of individual transport (more than 1,000 km), including cycling paths and pavements, and the railway transport network (inbound and outbound traffic) and tram network as well as the airport. The road network consists of the whole road system, including the sections of dirt roads that provide access to properties. To describe the demand side, the city was divided into 548 internal transport zones (Figure 3) and 19 zones that describe external traffic (including the airport).

Figure 2. Transport model map of the city of Bydgoszcz with marked roads [5]

The division into zones was carried out according to best practice applied in building transport models [6]. In the areas of more intense development, a more detailed division was applied (zones of smaller area), while in less urbanised areas, the zones are much larger. In addition, the boundaries of zones were delineated along natural obstacles (rivers, railway lines, hills). The basis for determining the demand side were questionnaires of transport behaviour of residents. The questionnaire was conducted as a direct interview and it included questions about the mode of transport during a trip on a day preceding the interview, within a so-called trip journal. A trip was accepted as the movement for minimum 100 m with the following motivations: home, work, education, shopping, shopping at shopping malls, and private matters. The questionnaire enabled to determine typical transport characteristics of residents, such as e.g. the division of lengths and time of travels with specific motivations and with determined means of transport, the number of trips, 24h distribution of trips, and the criteria of selecting means of transport for a trip. Such characteristics enabled the complete parametrization of the demand side of the model, and, with the description of the supply, the creation and calibration of a transport model. The calibration was based on the measurements of traffic carried out in parallel to the questionnaires conducted among residents. The sensitivity tests of the finished transport model proved that it operated correctly. The results of traffic volumes and passenger streams measured and obtained with simulations were on an acceptable level of conformity, as confirmed with the GEH statistics. The model developed in this way for the existing condition was applied to build prognostic models, where the numbers and boundaries of transport zones were not revised. Only some
of the descriptive data was changed, which characterised transport attractiveness, as a result of the planned changes to the area development in the city (new housing estates, new factories, swimming pools, shopping malls, etc.).

![Image of the city map with transport zones](image_url)

**Figure 3.** Transport model map of the city of Bydgoszcz with marked boundaries of transport zones

The above-mentioned models were used to prepare derivative models, based on the same description of the transport infrastructure (the supply part of the model), the same address database of traffic-generating facilities, but with a completely new division into transport zones. The new division into transport zones was prepared based on the original assumptions, namely that:

1. all zones have the same shapes — an isosceles hexagon — a so-called cluster;
2. zones are adjacent;
3. each zone has only one connection with the infrastructure of individual transport (individual transport as a driver or passenger in a car, private bicycle traffic) and one connection with the public transport infrastructure network (public transport or public bicycles);
4. the coordinates of the centre of gravity of a zone are determined as the weighted average of coordinates of traffic-generating facilities (buildings) according to the transport attractiveness of a facility according to the following formula:

\[
X_{coord_i} = \frac{\sum_{n=1}^{Q_i}((A_n+P_n)\times X_{coord_n})}{\sum_{n=1}^{Q_i} (A_n+P_n)} \\
Y_{coord_i} = \frac{\sum_{n=1}^{Q_i}((A_n+P_n)\times Y_{coord_n})}{\sum_{n=1}^{Q_i} (A_n+P_n)}
\]

(1)
where:
\( i \) – an ordinal number of a transport zone \( i \)
\( n \) – an index of a facility
\( O_i \) – the total number of facilities - trip origins and destinations of a transport zone \( i \)
\( A_n \) – attractiveness for a trip attraction of a facility \( n \)
\( P_n \) – attractiveness for a trip production of a facility \( n \)
\( X_{\text{coord}_i} \) – coordinate \( X \) of the zone gravity centre \( i \)
\( Y_{\text{coord}_i} \) – coordinate \( Y \) of the zone gravity centre \( i \)

5. the size of a zone (a radius of a hexagon — a cluster) is to be determined in such a way that minimum 95\% of their average distances between trip origins and destinations is not larger than the distance for which a trip has been defined (according to the assumptions of the questionnaires of transport behaviour of residents, a trip has been defined as movement between an origin and destination for minimum 100 m);

6. the distance between transport zones is calculated as the distance of the so-called connector and the distance of a route within individual transport or public transport;

7. the minimum distance between two zones equals the distance for which a trip is defined (see the above definition);

8. the distance from zone \( i \) to zone \( i \) (the demand matrix diagonal) is infinitely large (no trips inside a zone).

In line with the above-mentioned assumptions, an experimental method was used to select a radius of a transport zone for the analysed city area. As a result of consecutive approximations, it was concluded that with a radius of a hexagon of 125 m, for almost 96\% of all transport zones the average distance between trip origins and destinations did not exceed the distance of 100m according to the definition. Owing to this division, it was possible to allocate 2,265 internal transport zones. The allocated external zones have been kept according to the original definition in the base model, as external trip origins and destinations. A fragment of such defined transport zones has been presented in Figure 4.

5. Simulation tests
Simulation tests have used an analysis of a section of one of the essential roads in the city to be developed. The reconstruction of the section involves its extension to a dual carriageway road and building a bus lane. The cost of the whole investment project exceeds EUR 30 million. The project has gained co-financing from EU funds.

The purpose of simulation tests was to determine differences in the results of computing the traffic effects of the investment depending on the adopted division of the model area into transport zones. The comparison was based on the values essential for CBA, namely the vehicle-km and vehicle-h for the 25-years’ analysis period and the following computing scenarios:

\( S_0 \) – the scenario with no investment in the base model, without the reconstruction of the analysed section of the road, with the classical division into transport zones;

\( S_1 \) – a scenario in the base model, with the reconstruction of the analysed road section to the dual carriageway road, with an additional bus lane and traffic lights at crossroads, with the classical division into transport zones;

\( NS_0 \) – the scenario with no investment in the base model, without the reconstruction of the analysed section of the road, with the classical division into transport zones;

\( NS_1 \) – the scenario with the investment in the base model, with the reconstruction of the analysed section of the road as in scenario \( S_1 \), with the classical division into transport zones.

For all the above-mentioned computing models, the most popular calculation procedure was applied, generally used in transport model simulations, according to the four-step process of recreating transport processes. Hence, the following processes were recreated:
Figure 4. A fragment of a transport model of Bydgoszcz with marked boundaries of transport zones applied in simulation studies

a) traffic generation (the start of a trip within a trip motivation) — the number of generated trips per given time interval of analysis is constant, regardless of a computing scenario;
b) the spatial distribution (the selection of a destination location) — the spatial distribution of trips between transport zones in the function of their transport attractiveness and spatial trip resistance (trip distance, time, cost etc.);
c) the mode choice (the selection of the mode of transport) to take trips within a given motivation;
d) the assignment of transportation demands into a transport network (private network, public transport network etc.) — the designation of probable routes of trips between pairs of zones and then road and street loads as well as load on means of public transport with vehicles and passengers.

It is noteworthy that both in scenarios S0-S1 and NS0-NS1, the same available transport network was defined, being a supply part of the analysed models, including almost 940 km of roads and 64 lines of public transport of the total transport work of almost 53,500 km/day. Considering the new planned transport investments as well as changes in the area development in all scenarios, the same transport investments were defined and the same changes within transport systems. The results of simulation tests for scenarios S0 and S1 for individual transport have been presented in Table 2, and for scenarios NS0 and NS1 in Table 3. The differences in modelling results of vehicle-km and vehicle-h values between scenarios (NS1 – NS0) - (S1 – S0) as the difference in investment effects have been presented in Table 4.

According to the results of simulation analyses, transport models with a higher number of transport zones indicate the 7-8% increase of traffic indices that are the basis for the efficiency assessment of a transport investment project. Such differences may reach the value of even about a dozen per cent, which means that the calculations in the original scenario underestimated substantially the economic efficiency
of the investment. The cause of such differences may include first of all the deficiency of original models, which involves their simplifications that result in:

**Table 2.** Results of simulation calculations for scenarios S0 and S1 in private transport

| calculation scenario | forecast year | veh-km    | veh-h    | passengers | pass.km | annual daily traffic |
|----------------------|---------------|-----------|----------|------------|---------|----------------------|
| S0                   | 2017          | 3,627,648 | 103,333  | 554,343    | 4,752,219 | 3,022                |
|                      | 2020          | 3,723,165 | 83,007   | 564,367    | 4,858,731 | 3,037                |
|                      | 2025          | 3,812,946 | 84,039   | 577,596    | 4,956,830 | 3,099                |
|                      | 2030          | 3,953,562 | 87,020   | 596,411    | 5,100,095 | 3,201                |
|                      | 2035          | 4,062,811 | 89,304   | 610,824    | 5,159,770 | 3,275                |
|                      | 2040          | 4,088,552 | 88,871   | 612,787    | 5,151,576 | 3,260                |
|                      | 2045          | 4,032,869 | 87,130   | 596,000    | 5,041,087 | 3,213                |
|                      | 2050          | 3,950,709 | 84,588   | 576,121    | 4,898,879 | 3,148                |
| S1                   | 2017          | 3,623,027 | 102,995  | 553,432    | 4,746,165 | 3,018                |
|                      | 2020          | 3,717,819 | 82,701   | 563,352    | 4,851,754 | 3,033                |
|                      | 2025          | 3,809,997 | 83,834   | 576,743    | 4,952,996 | 3,097                |
|                      | 2030          | 3,952,878 | 86,923   | 595,921    | 5,099,212 | 3,201                |
|                      | 2035          | 4,055,614 | 88,638   | 610,514    | 5,150,630 | 3,269                |
|                      | 2040          | 4,086,982 | 88,726   | 612,633    | 5,149,597 | 3,258                |
|                      | 2045          | 4,030,249 | 86,978   | 595,828    | 5,037,811 | 3,211                |
|                      | 2050          | 3,949,428 | 84,464   | 575,948    | 4,897,291 | 3,147                |

**Table 3.** Results of simulation calculations for scenarios NS0 and NS1 in private transport

| calculation scenario | forecast year | veh-km    | veh-h    | passengers | pass.km | annual daily traffic |
|----------------------|---------------|-----------|----------|------------|---------|----------------------|
| NS0                  | 2017          | 3,903,349 | 112,220  | 554,343    | 5,113,388 | 3,252                |
|                      | 2020          | 3,994,957 | 89,814   | 564,367    | 5,213,418 | 3,259                |
|                      | 2025          | 4,087,478 | 90,846   | 577,596    | 5,313,722 | 3,323                |
|                      | 2030          | 4,242,172 | 94,165   | 596,411    | 5,472,402 | 3,435                |
|                      | 2035          | 4,363,459 | 96,654   | 610,824    | 5,541,593 | 3,517                |
|                      | 2040          | 4,395,193 | 96,203   | 612,787    | 5,537,944 | 3,504                |
|                      | 2045          | 4,343,400 | 94,344   | 596,000    | 5,429,250 | 3,461                |
|                      | 2050          | 4,270,716 | 91,652   | 576,121    | 5,295,688 | 3,403                |
| NS1                  | 2017          | 3,898,015 | 111,832  | 553,432    | 5,106,399 | 3,248                |
|                      | 2020          | 3,989,108 | 89,457   | 563,352    | 5,205,786 | 3,254                |
|                      | 2025          | 4,084,221 | 90,598   | 576,743    | 5,309,488 | 3,320                |
|                      | 2030          | 4,241,161 | 94,040   | 595,921    | 5,471,098 | 3,434                |
|                      | 2035          | 4,355,689 | 95,915   | 610,514    | 5,531,725 | 3,511                |
|                      | 2040          | 4,393,383 | 96,019   | 612,633    | 5,535,662 | 3,503                |
|                      | 2045          | 4,340,498 | 94,145   | 595,828    | 5,425,622 | 3,458                |
|                      | 2050          | 4,269,253 | 91,489   | 575,948    | 5,293,874 | 3,402                |

a) omitting a part of the internal traffic that affects traffic conditions on roads (including on crossroads);
b) omitting the time and distance in internal trips;
c) the improper and oversimplified realities of zone connections to a transport network.
Table 4. Differences in results of simulation calculations between scenarios (NS1 – NS0) - (S1 – S0) in car transport

| calculation scenario | forecast year | veh-km | veh-h | passengers | pass.km | annual daily traffic |
|----------------------|---------------|--------|-------|------------|---------|----------------------|
| (NS1 – S1) - (NS0 – S0) | 2017          | -714   | -50   | 0          | -935    | -1                   |
|                      | 2020          | -502   | -50   | 0          | -655    | 0                    |
|                      | 2025          | -308   | -43   | 0          | -400    | 0                    |
|                      | 2030          | -327   | -27   | 0          | -421    | 0                    |
|                      | 2035          | -573   | -73   | 0          | -728    | 0                    |
|                      | 2040          | -240   | -39   | 0          | -303    | 0                    |
|                      | 2045          | -282   | -47   | 0          | -353    | 0                    |
|                      | 2050          | -183   | -37   | 0          | -227    | 0                    |

6. Conclusions
Simulation transport models are the basis for generating data that indicates the efficiency of transport investments. Moreover, the local impact of transport investments cannot be determined with methods other than network simulations, where the analysis covers flows of vehicles and public transport passengers in the functions of demand and supply. This study presents only the differences within the modelling effects for two accuracy conditions of the transport attractiveness description in individual transport. Due to the scope of results, no analogous analyses were presented for public transport. The identified factors, which cause the differences in the effects of model analyses, are probably not the only ones. The research hypothesis of the paper has been initially confirmed. However, further simulation tests are required, in order to show how important errors in the generated results are, and thus how they affect the results of the costs and benefits analyses of transport investments.

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