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Simulation Analysis of CO_2 Emission for Different Land Use Development Schemes

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Abstract

This study demonstrates possibility of simulation software application to modeling level of CO_2 emission as a result of different land use development scenarios as well as different level of private and public transport investments in the city. Application of simulation software Visum and four stage approach for transportation model of Krakow agglomeration gives detailed information about influence of different policy directions onto CO_2 emission in the city. This paper is focused rather on estimation of the vehicle kilometer travelled (VKT) then on modeling emission procedure and shows effects of different assumptions in planned transportation policy on emission level.

1. Introduction

Dynamic development of city substances, observed especially during recent decades has strong influence on functional aspects of street networks. New living areas, supermarkets or industrial areas are significant traffic generators which imply changes into functioning both public and private transportation. Very often existing street networks, especially in historical cities, are not prepared for high levels of traffic. Those problems refer also to districts which are placed outside the downtown areas – in the suburbs. Many times housing estates are connected with street networks through few streets with low technical parameters. It's affect on increasing lost time of passengers (and drivers), increase operating costs, influence on modal split (by decreasing share of public transport) and decrease the level of life in cities.

Another problem is the effect of city sprawling, which can be observed in many Polish cities. Mostly it is the reason due to the high price of the apartments in the downtown area and that tendency has been escalated during the last few years. The

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main problem, from a transportation point of view, is increasing the length of the trip in agglomerations and difficulties in planning of public transport service in the suburbs (low density of population together with long distances implies lack of service effectiveness and forced inhabitants to use private cars).

In reply to the increasing number of building investments and displacement of traffic origins and destinations, city authorities are planning and implementing many infrastructure investments and heading for modernization and development of public transport system. Those investments fulfilled demands and assumptions of sustainable development policy and results of them can be quantified in proper designing documentation (e.g. feasibility study).

Transportation policies of agglomerations are mostly based on sustainable development principles which are presented e.g. in the "White Paper" book [18]. They are not restrictive for private transport, but focus on encouraging inhabitants to use public transport modes. Each city has reached the state of equilibrium between those two modes of transport, and the main goal of the planned development of the city is to decrease the share of private transport among non-pedestrian trips. Public transport priorities, separated bus lanes, access restrictions, congestion charge, Park and Ride, car-pooling, car-sharing and many others tools can be used to reduce and rationalize private transport demand and in the effect to reduce traffic congestion. Transportation policy is not solving actual problems but presents main direction of the future policy. It is difficult to assess the impact of planned activities and to quantify results of introduced measures but still possible. Within this paper it will be presented a procedure of verifying different scenarios for land use development changes as well as for different levels on investment in private and public transport. These analysis will state the base for estimation of CO_2 level as a chosen environmental parameter.

2. Description of the Simulation Model

The purpose of this paper was to use the simulation model of the Krakow defined in VISUM software for estimation of CO_2 emission level for different land use development schemes. The model is based on results of Comprehensive Travel Study (conducted in Krakow in 2003 [6] and 2007 [7]) and is embedded in traditional four step approach:

- Trip generation: according to obtained results of Comprehensive Travel Study (CTS), it was possible to define the relationship between generated trips and spatial development (described as number of inhabitants, working places etc.) for different trip purposes. The main result of this stage are linear regression functions which were used to calculate number of trips generated in assumed traffic zones.

- Trip distribution: the result of this stage is the O-D matrix (origin – destination) showing spatial distribution of generated trips in the city. The gravity model defined by logit model calibrated for the city in the frame of CTS was used.
- Modal split: according to results of the mobility survey, it was possible to define the modal split model for Krakow. The model has logit character, but the compliance with results were insufficient. As the influence factor was the chosen quotient of travel times for public and private transport, but the results relevance to the survey were rather low (determination rate R^2 =0,34). Nevertheless for further calculation author's model of modal split [13] based on quotient of generalized cost of the private and public transport trips was used (description below).
- Assignment: it was defined street network model of Krakow (in Visum software), and after applying assignment procedure (Stochastic assignment) it was possible to define traffic volume at links.

2.1. Modeling of modal split

The most important part of the model was application of modal split model. This approach is based on Mamdani Fuzzy Inference System - FIS [13]. In general, to compute the output of FIS, the following six steps should be fulfilled:

- determining a set of fuzzy rules;
- fuzzifying the inputs using the input membership functions,
- combining the fuzzified inputs according to the fuzzy rules to establish a rule strength,
- finding the sequence of the rules by combining the rule strength and the output membership function,
- combining the consequences to get an output distribution,
- defuzzifying the output distribution (this step is only if a crisp output is needed).

For our case a Fuzzy Inference System with one input and one output set was used. Share of PrT among non-pedestrian trips depends on value of quotient Δ:

$$\Delta = \frac{K_{\Pr T}}{K_{PuT}} \tag{1}$$

where:

KPrT – generalized cost of the trip of private car;

KPuT – generalized cost of the trip of public transport;

For further analysis as a symbol of quotient of generalized cost of the trip, will be used symbol "*quotient PrT/PuT*". Assumed input data ("*quotient PrT/PuT*") requires choice of linguistic variable [16]. Values of linguistic variables are called terms and can be described as "*small*", "*large*", etc.

In this case the linguistic variable is proposed as follow:

Δ ("quotient PrT/PuT")=["very small", "small", "equal", "large", "very large"]

For each term it is necessary to define shape of membership function (MF). Due to lack of the data, one has decided to use experts' inquiries (sample size: 40). Due to significant value of standard deviation it was necessary to conduct inquiries for the second time – using Delphic approach (the same group of experts received results of first questionnaire and had to create their own membership function which fit the area between upper and lower quartile).

As an output data there will be taken linguistic variable U ("share"), described by following terms:

U("share")=["small", "medium", "large", "very large"]

Range for values of linguistic variable "*share*" were defined according to results of existing bimodal functions for Polish cities. Membership function for variable "*share*" was estimated in the same way as variable "*quotient PrT/PuT*".

Last element of Fuzzy Inference System is to define semantic rules which are based on implication IF...THEN. E.g. IF "*quotient PrT/PuT*" is "*very small*" THEN "*share*" is "*small*". It was created set of all possible rules. Next step was to verify rules which are not possible or illogical and then reject them. Then for some less important rules there were assumed proper weights.

The scheme of applied Fuzzy Inference System is presented on Fig. 1:

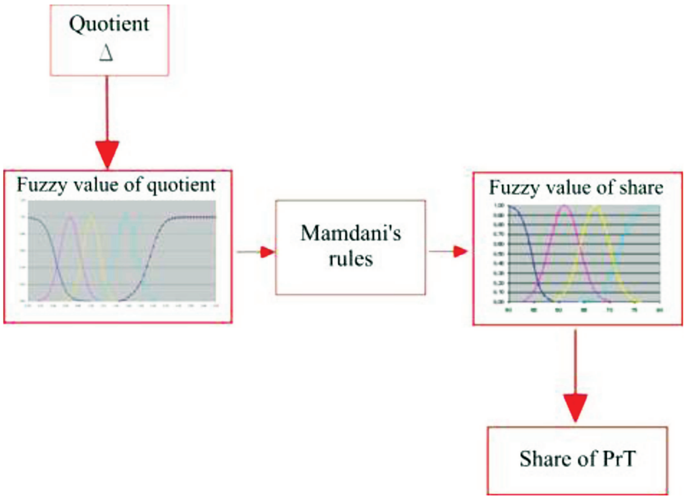

Fig. 1. Scheme of FIS defining share of PrT

The effect of running fuzzy inference process is presented as a two dimensional chart. To compare results of fuzzy process with existing logit models it was necessary to approximate it. Using Mathematica software [17] there was proposed empirical function:

$$U'_{\Pr T} = 65,2 * \Delta^{0,11} \tag{2}$$

Presented procedure was treated as iteration process, repeated several times to obtain better values of relevance (calibration process was based on comparison traffic counts and modeled traffic volumes on selected links in the network – 142 count locations in the city). The process of model calibration was focused on network parameters and afterwards it was obtained coefficient R^2 =0,72 which was treated as acceptable for further work. Results of the assignment are presented on Fig. 2.

Fig. 2. Results of assignment procedure in simulation model of the Krakow Agglomeration during afternoon peak hour (2010) [veh/h]

2.2. Demand forecast

Based on the calibrated model for 2010 it was created a forecast for 2030. For this purpose it has been taken another set of assumptions, regarding both supply and demand level:

- **Supply** – it was assumed, that network will change according to investments which were approved or planned in 2010. Investments taken into consideration refer both to public and private transport systems. The mutual impact of private and public modes of transport was estimated via application of the modal split procedure.
- **Demand** – for the purpose of future OD matrix estimation were used formulas based on CTS 2003 and 2007, but final values of trips generated by traffic zones were then changed according to estimated mobility balance. This procedure assumed, that mobility rate in non home based trips will increase in prognostic horizon (home based trip rates will not significantly change) and this gives the total increase of mobility rate from 2,02 [trips/day/inhabitant] to 2,85

[trips/day/inhabitant]. It was of course individual assumption, but according to trends observed in European countries – seems reasonable.

The most important data which states base for forecast analysis refer to changes in spatial land use development. These changes were illustrated by different numbers of inhabitants, students, employees, working places etc estimated for each traffic zone and vary development directions. For this purpose it was assumed three scenarios for different directions of land use changes [12]:

- Land use data changes according to the Land Use Development Plan for Krakow, in which changes in value of variables vary according to political decisions of future development of the city – **LUDP**;
- Land use changes will take place only for zones located in the transportation corridors – **TC**;
- Land use changes will be implemented in all traffic zones, with no relationship to location of transportation corridors – this variant was called decentralized – **DC**.

For each scenario it was calculated full simulation model in order to obtain traffic volume on links. It is worth emphasizing, that for each scenario (taking into consideration both supply and demand changes) impact was calculated of planned transportation investment in the city.

3. Emission Calculations

To estimate level of emission, it is possible to apply plenty of different approaches verified on real data. There are lots of different manuals [1, 16, 17, 18] or papers presenting applications of different methodologies [21, 19]. In [9] impact of different control strategies on level of emission was estimated. In [10] it was shown the impact of different land use schemes on emission levels based on historical data and [14] pointed out was the link between land use development and applied transportation systems. The need for finding the relationship between different land use development schemes and expected environmental impact of such decisions is defined and presented as a supporting tool on future decisions. The process of modeling emission level requires broad sets of data concerning rolling stock, however the most important data are not connected with model parameters (which are widely described in many publications) but estimation of traffic volume on the streets in analyzed area.

The main goal of this paper is to show the impact of different future land use schemes onto CO_2 emission. These analysis would be helpful for decision makers to conduct transportation policy in such away, that expected impact of transport on environment will be minimized. Estimation of emission (CO, NOx, CO_2 etc.) requires application of advanced formulas calibrated to certain conditions. In the case of CO_2 emission it is possible to apply several procedures but all of them are based mostly on traffic volume, traffic composition, average speed of vehicles, share of different engine types and kind of fuel. According to [3] estimation of emission can be calculated using following polynomial with 5^{th} degree:

$$E = a + bx + cx^2 + dx^3 + ex^4 + fx^5 \tag{3}$$

where:

E – emission level of the single vehicle on the link [g/km],

a,b,c,d,e,f – parameters determined separately for different pollutants for cars and trucks for the year 2010,

x – speed of vehicles [km/h].

The parameters of the model are changing according to the speed changes. On the Fig. 3 it is presented example of trend for cars (in reference years) and trucks for carbon monoxide emission level [19].

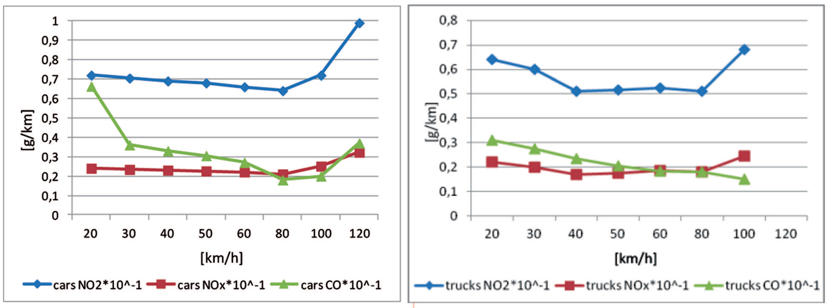

Fig. 3. Emission volume in g/km for different vehicle types and different pollutants

To obtain the value for whole street or full network, it is necessary to take into consideration **vehicle kilometers travelled** (VKT) parameter, estimated separately for each group of vehicles. That is why some approaches take into consideration more parameters. To estimate total CO_2 emission level for the entire study area the following multiplication formula could be used[11]:

$$E_{TC} = \sum_{1}^{N} (F_{SV} \cdot D_{SV} \cdot C_{SV}) \tag{4}$$

where:

E_{TC} – total CO_2 emission [g] for a given vehicle type v,

N – number of street segments – links,

F_{sv} – the traffic flow on a link and corresponding type of vehicle,

D_{sv} – the distance travelled on a segment of road by a given type of vehicle,

C_{sv} – the CO_2 emission factor [g/km] on a link for a given vehicle type and speed.

To simplify calculations appropriate software can be used e.g. COPERT 4 [2] which estimates level of emission for plenty of substances using actuated values of parameters. However, mentioned approaches require detailed information about traffic and its composition for the full network. In case of simple analysis, focused on few streets, it is possible to conduct traffic survey and collect necessary data. But for the whole transportation network, it necessary to apply simulation software and full transportation model for appropriate emission calculation. In the second chapter of this paper simulation model and chosen land use scenarios was describe. The simulation model has significant simplifications, e.g. is focused only on private transport (with one, constant in each scenario OD matrix for Heavy Good Vehicles). For this purpose it was necessary to fix certain assumptions concerning CO_2 emission calculation: traffic composition on links was averaged as well as type of fuel, the engine capacity share and year of the rolling stock. Based on [5] it was assumed, that average emission of CO_2 for forecast purposes is equal to 92 [g/VKT] – it is also requirement for vehicles produced after 2020, according to requirements of European Commission (VKT – Vehicle Kilometers Travelled). Assumed value of CO_2 emission is averaged and will be used only to compare impact of different land use scenario on level of CO_2 emission. For detailed calculations it will be necessary to estimate parameters which here have been simplified.

4. Simulation Results for Different Land Use Development

Each simulation scenario was calculated in Visum software and the VKT parameter was then assigned. Table 1 presents results of the simulations for all scenarios:

Table 1

Results of simulation for analyzed scenario [vehkm]. Result refers to one hour of afternoon peak period simulation

Scenario	VKT [vehkm]
Land Use Development Plan **LUDP**	**4 192 000**
Transportation Corridors **TC**	**4 006 000**
Decentralized **DC**	**4 112 000**

Based on assumptions concerning traffic composition on links, share of different types of fuel, the engine capacity and year of the rolling stock it was possible to estimate level of CO_2 emission for whole agglomeration Fig. 4.

In this approach, level of emission is in simple relation to VKT, so results were predictable: for the scenario with the land use development change within transportation corridors (**TC**) the level of emission achieved the lowest value. This is the result of shortening trips due to extensive development of areas with better transportation accessibility. This affects less trip distance and in the result less value of average trip length. In other scenarios values of emission are not significantly higher, but the difference is noticeable. It is worth emphasizing, that in decentralized

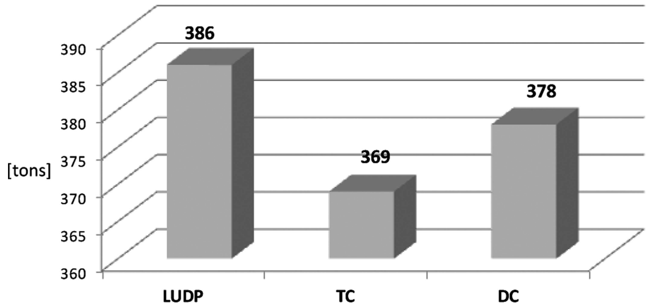

Fig. 4. Estimated mass of CO_2 emission for Krakow agglomeration during one afternoon peak hour of the simulation [tons]

scenario (**DC**) we would expect the worst results, but they were a bit better than for **LUDP** scenario. It means, that it is recommended verification of LUDP assumption on order to minimize future level of transport absorption which affect future CO_2 emission.

5. Simulation Results for Different Levels of Infrastructure Investments

Conducted simulations were calculated according to one scenario of transportation system development – for each scenario it was assumed the same investments both for private and public systems. For further calculations it was assumed more detailed premises concerning level of transportation investments and its effect on modal split. It was chosen one scenario for further analysis – for decentralized land use development calculated demand it was defined four variants:

- **Variant 1** – maximum level of private transport network development – according to official planning documents [12], [8] and minimum level of public transport infrastructure development (in this case there were only investments for which formal procedures of building permission were running in 2011 chosen). The crux of the concept is to implement well developed road network, especially finalizing full ring road investments and many missing links filling up the gaps in existing road network of the city. In term of public transport investments, it was assumed refurbishment of chosen tram lines (to increase the averaged speed of trams) and building up only few new tram connections. Developed fast tram network was limited only to direction South-North. This variant was created to show what will happen if infrastructure investment effort will be directed only on private transport needs;
- **Variant 2** – both transportation systems (private and public) were invested on averaged levels – there were only highly feasible investments chosen. The dif-

ference between this variant and the first one is number of investments. In first variant it was assumed all possible investments even if the feasibility of them was not proved. In this case it was assumed to have only the most reliable road investments (e.g. the north bypass was not taken into consideration) and public transport ones. Chosen variant has averaged and sustainable character;

- **Variant 3** – public transport oriented variant. Only the most probable private transport investments and all planned public transport ones were taken into consideration. It is rather theoretical variant, where road investments were limited only to the most reliable ones (as taken in variant 2) but for public transport investments there were taken all planned tram tracks (both refurbished and built), revitalization of local rail system and development of fast tram;
- **Variant 4** – reliable public transport oriented. For this variant it was assumed to have minimum level of private transport investments (as it was chosen for Variant 3) and the most important and probable public transport ones. In this case the investments taken into consideration in Variant 3 were verified and there was chosen only the most probable ones, like modernization of tram corridors, development of fast tram system and new tram tracks.

Application of different network investments had significant impact on modal split in the city. For the purpose of precise analysis of the simulations, it was estimated share of different trip modes both for whole model and for smaller area, located in the city centre. In the Table 2 it is presented values of modal split for each scenario.

Table 2

Estimated modal split for different level of infrastructure development

Analysed variant	Level of investment development		modal split – whole agglomeration	modal split – city centre
1 Variant	PrT*	Maximum	**60%**	**40%**
	PuT*	Minimum	**40%**	**60%**
2 Variant	PrT	Averaged	**47%**	**30%**
	PuT	Averaged	**53%**	**70%**
3 Variant	PrT	Minimum	**46%**	**30%**
	PuT	Maximum	**54%**	**70%**
4 Variant	PrT	Minimum	**33%**	**20%**
	PuT	Averaged	**67%**	**80%**

*) PrT – private transport; PuT public transport

For each variant it was conducted proper simulations using simulation model described in chapter 2. As a result it was obtained values of VKT both for whole agglomeration and for assumed area of city centre. Figure 5 presents results of simulations (in tons of CO_2) calculated for each variant on the basis of VKT.

The level of CO_2 emission is decreasing (which was expected) if we assume more investments in public transport networks than in private ones. These differences

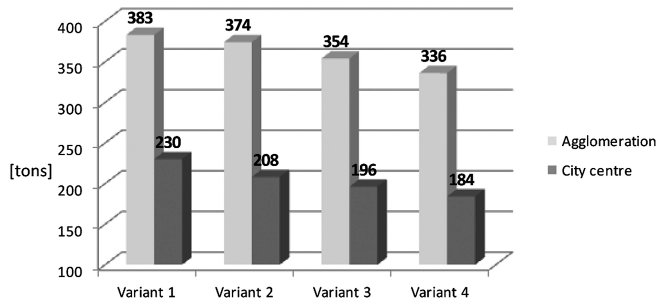

Fig. 5. Estimated mass of CO_2 emission for analyzed variants – results refers to one hour of simulation period for afternoon peak hour [tons of CO_2]

are even more significant especially for city centre, where the difference between the worst and the best investment levels are over 25% (46 tons of CO_2 less in the city centre for variant 4 in comparison to Variant 1). For the whole agglomeration the results are not so significant, but still noticeable – over 13% between 1^{st} and 4^{th} variant. It is worth to emphasize, that there is small difference between 3^{rd} and 4^{th} variant for the whole agglomeration (approx. 5%), which means that when we assume minimum level of private transport investment development and maximum or averaged level for public transport system development, it will not have significant impact on levels of emission. The difference inside the city centre is slightly bigger but still do not exceed 7%.

6. Conclusions

Simulation analysis of different land use development schemes are widely used tools supporting political decisions. Within this paper, the analysis were aimed on estimation CO_2 emission levels which derive from calculated vehicle kilometers traveled in the simulation model of Krakow agglomeration. The most important goal was to assume different scenarios and variants and for calculated VKT which states the basis for simplified estimation of CO_2 level. In this paper it was assumed three scenarios of different schemes of demographical changes within the agglomeration and four variants of different levels of transportation system development.

In the case of demographical change scenarios, results of the simulation give us the information about risk in planned (assumed by politicians) directions of demographical development and shows advantages of demographical activation within transportation corridors – the difference in CO_2 emission is almost 5% lower. When we assume share of afternoon peak hours equal to 8,35% (according to travel study in Krakow), and number of working days in a year equal to 300, in this case we can obtain over 61 000 tons of CO_2 per year less than in the case of LUDP scheme.

Very interesting results were obtained for analysis of different levels of investment in transportation systems. As it was expected, the lowest CO_2 emission was for variants with well developed public transport investments in comparison to private transport oriented variants. From an agglomeration point of view, levels of public transport investments are slightly less important and for the city centre the difference is bigger: with yearly assumptions mentioned above, the difference in CO_2 emission between variant 3 and 4 is over 43 000 tons CO_2 per year! Even more significant differences refer to the 1^{st} (private transport oriented) and 4^{th} variant (public transport oriented). In this case the differences in CO_2 emission exceed 165 000 tons CO_2/year in the city centre.

Conducted analysis were simplified in terms of proper estimation of CO_2 emission – mostly it is the result of plenty of simplification in the transportation model and lack of detailed data which are necessary in full approach. However obtained results are important from a transportation planning point of view and could be useful as a support tool in important decisions which affect future developments of the city.

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