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KÁLMÁN KANDÓ DOCTORAL SCHOOL OF TRANSPORTATION

AND VEHICLE ENGINEERING

MATHEMATICAL MODELING OF COMPLEX ECONOMIC EFFICIENCY METHODS OF INTELLIGENT DEMAND RESPONSIVE PUBLIC TRANSPORT SYSTEMS

overview of Ph.D. thesis

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1. BACKGROUND AND ACTUALITY OF RESEARCH STUDY

4,8 % of European GDP (548 billion €) comes directly from the transport sector which also means workplaces for 11 million people. Increasing the energy efficiency is crucial because it is connected to most of the high lightened transport challenges (congestions, oil dependence, emission of greenhouse gases, quality of infrastructure and opening up transport markets to free and undistorted competition). In 2012 the European Parliament published a discipline which shows the opportunities to reach the EU 20-20-20 goals. The role of transport in this topic is unquestionable that is why the EU supported a lot of project which dealt with the theoretical and practical sustainable transport.

Demand responsive transport systems (DRT) can be an optimal tool for energy efficient and sustainable transport. DRT systems generally use microbuses in a capacity efficient way which also means energy efficiency. If this attribute meets green technology DRT systems are very competitive in environmental effects. These systems are flexible in time and spare which means they can adapt well to the locational conditions and to the demands of local people.

On the other hand, DRT systems would not be able to serve the transport demands of a big city (like Budapest) because of the dynamic passenger check-ins and the number of standby vehicles and drivers. Their advantages can be realised in sparsely populated areas and in collecting or distributing structures. We should find the borderlines of social and economic parameters that show whether it is worthy to operate a DRT system in a city or not. LTP-s (local travel plans) and SUMP-s (sustainable urban mobility plans) can help finding these borders to identify the exact attributes of the needed DRT system.

2. OBJECTIVE

Pricing is a crucial point when we investigate the utility and the applicability of DRT systems. On one hand the pricing should be fair and equitable but on the other hand pricing defines the incomes of the operator. My objective is to create a flexible pricing system for DRT systems which is transparent and motivate passengers to invite other potential passengers.

After having a pricing system, it is possible to deal with the CBA (cost benefit analysis) of DRT systems. The identification of externalities is critical to understand the social benefits and costs. I participated in the Hungarian pilot project of the ForFITS software (developed by the UNECE). Our aim was to collect Hungarian data to the programme as an input to investigate the 30-year forecasts of CO_2 emission based on different scenarios. These scenarios differ in political strategies which means that ForFITS helps politicians to see the long-term consequences of their decisions. I investigated ForFITS programme whether it is applicable to detect the differences between a scenario with DRT systems and a basic scenario without them. These differences (in energy use and in CO_2 emission) are also inputs for the CBA.

Beyond the calculation of externalities, in a transportation project we need estimation methods to forecast how many people would use a new system and how the modal split would change. The main aim of the dissertation to identify a transport utility function and to create a method that can estimate the changes of modal split by the utility function.

3. METHOD OF THE RESEARCH

The first step was the research of literature: I looked over the Hungarian and international journals in the topics of DRT systems, pricing systems, stated preference method and utility functions. I got essential information about operating DRT services from the operators' websites.

In the case of pricing systems, I made simulations to show the differences in DRT services. In these simulations, it is transparent how the new pricing system would work.

The model of ForFITS was created in Vensim environment so I had to be familiar with the basic usage of Vensim. The input system was based on MS Excel so the collected data was written in regular tables. In the Hungarian pilot project, we used KSH data, European statistical books and own structured surveys as a resource.

To identify the transport utility function, I created a fictive case study. I used stated preference method in this fictive environment to create surveys. The full factorial design of stated preference method was made by mathematical combinatorial methods and then it was optimised by an own way to make the survey more user friendly and reliable. The main context of the stated preferences was examined by the tools of mathematical statistics. I used the statistical module of MS Excel for the correlations and hypothetic independency investigations.

The dissertation used the steps of Cost-Benefit Analysis which was created by the European Union and translated by COWI[1]. Although the planned DRT service was not investigated by net present value (NPV) and internal rate of return (IRR) - as it was suggested by the guide – the dissertation showed the logical thread of applying CBA for DRT systems. This also means that it is possible to make the real calculations with NPV and IRR indicators.

[1] Trenecon (COWI): Guide to Cost-Benefit Analysis, 2016

4. New Scientific Results

In the twentieth century time (and the value and benefit of time also) was in the centre of mobility processes. In the twenty-first century humanity became more and more important. It is not enough nowadays to calculate the direct benefits of one passenger but we estimate the indirect effects on other passengers, other users of different travel modes, on the living area and on the environment. These points of views try to integrate economic, social, environmental consequences to defend the values of whole community. In Hungary, we still have difficulties because of old time political strategies but because of the European disciplines and guidelines there are good examples for building sustainable and liveable urban areas.

DRT services are innovative opportunities to make our transport system more sustainable. On one hand DRT services have better conditions then the individual modes of transport: more cost-effective operation, better use of land, better use of capacities, more effective energy consumption and sometimes the minimum requirement of entering the market. On the other hand, DRT services can overfulfil the traditional public transport services in economic, environmental and technological ways as it has better indicators in capacity effectivity. Better capacity effectivity also means better effectivity of energy use, less damage of the environment, less accidental risk and better land use. DRT systems can adapt better to the demands of people which means they have a higher level of service because passengers might feel more comfortable, might walk less to get on the DRT bus and might have shorter travel time.

But DRT systems have their borders as they would not be able to solve the transport demands of a big city (like Budapest). The uncertainty of two million people would result in an enormous number of stand by buses and drivers which would be hard to handle and would not be cost effective. That is why it is needed to find the social and economic borderlines where the use of DRT services becomes more effective than the traditional public transport (mainly in sparsely populated areas or as a complement of traditional services).

4.1. New Scientific Results

1. I disclosed that combining average cost based pricing and marginal cost based pricing meant the most effective pricing system for the society at DRT systems.

DRT systems usually have flexible routes and flexible timetable which means that the pricing system would also have to be flexible somehow to handle the demands in a fair and equitable way. Based on existing systems I created a mixed pricing system. The basic of this system is a dynamic average cost based pricing where the focus of the calculation is "loop cost". But there are cases when loop cost based pricing is disadvantageous so in these cases the mixed system uses marginal cost as a base (Figure Figure 1).

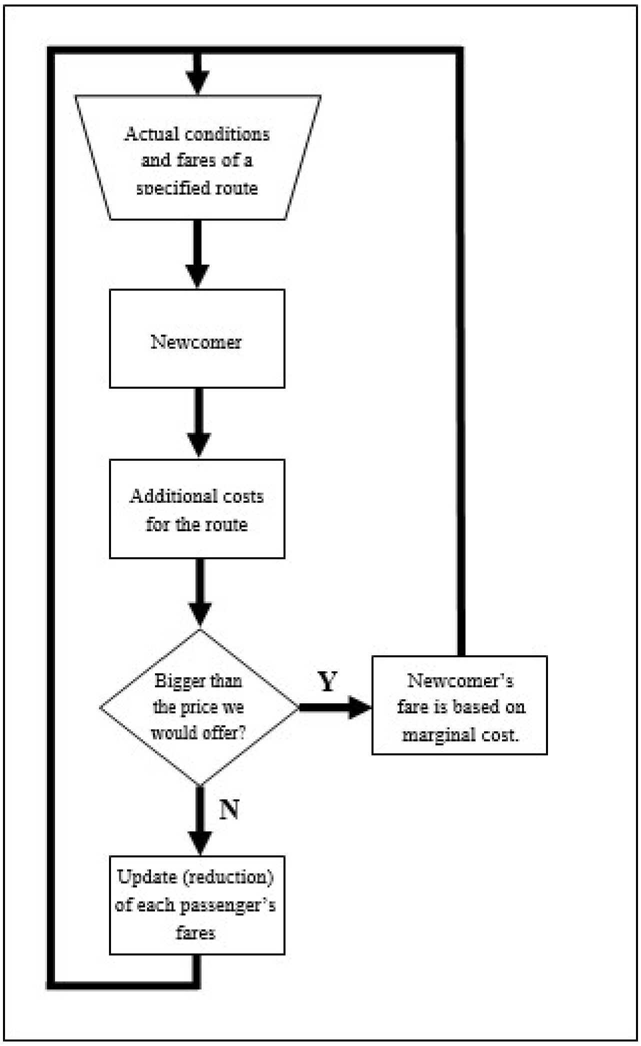

Figure 1: The process of mixed pricing (own editing)

(1) $$p_n = \max\left(TC_n * \frac{c_n}{\sum_{i=1}^{n} c_n} \; ; \; TC_n - TC_{n-1}\right)$$

(2) $p_1 = c_1 = TC_1$, where:

- n: actual number of passengers in the shuttle;
- p_n = the fee to be paid by passenger “n”;
- c_n = the loop cost of passenger “n”;
- TC_n = the collecting loop cost for n passengers (the cost of shuttle that should be distributed).

The new system must have a dynamic way of passenger information system to communicate the actual prices which are the actual fairest and most equitable possibilities. But with these system, we can concentrate also to the economic and operational points of views. The other advantage of mixed pricing is that passengers are motivated to inform the operator as soon as possible and involve other similar passengers because they might have less fees.

Publications by the author related to the thesis: (Andrejszki and Török, 2012), (Andrejszki and Török, 2014b), (Andrejszki and Török, 2015)

2. I disclosed that statistical forecasting and back-casting should be used together in decision support to make the results more reliable because of the complexity of transport system.

Although more and more statistical analysis’s of the transport related telematic systems are available because of the development of informatic technology, the traditional models of forecasting cannot handle the political turn-offs.

Back-casting identifies the curve that connects the midterm and long-term political targets with the actual situation. The method of forecasting should be complemented by the tool of back-casting. With this complement forecasts (which are based on past tendencies) would be able to be a more reliable tool for decision makers to build the most realistic and most achievable timeline of development.

Publications by the author related to the thesis: (Baranyai et al., 2015a), (Baranyai et al., 2015b)

3. I disclosed that ForFITS software (which was developed by the UNECE and our Department leaded the Hungarian pilot project of it) is suitable for the complex modelling of the modal shift of public transport, therefore the forecasts become comparable with the political targets.

For the first step ForFITS gives a 30-year-long forecast based on past and present data and in the condition of not changing political attitude. The results are performance and emission indicators for each transport sector of a country. The input data have four levels as some of them are needed by the user but some of them are estimated by the programme itself if the user does not have the needed punctuality.

The final product of ForFITS is a 30-year-long forecast of WtW CO_2 emission (Figure Figure 2) which is based on the ASIF equation. In the extended formula, the elements A (activity), I (energy intensity) and F (fuel/carbon intensity) are included and modal shares (S), are omitted, so that in fact an A(S)IF approach is applied. In this case, the ASIF equation is extended as it is shown in equation 3 and 4.

(3) $$\sum_i F_i EF_i = A\sum_i \left(\frac{A_i}{A}\right)\left(\frac{F_i}{A_i}\right)\left(\frac{EF_i}{F_i}\right) = A\sum_i S_i I_i EF_i = E$$

With:

(4) $$EF_i = \sum_j \left(\frac{EF_{ij}}{F_{ij}}\right)\left(\frac{F_{ij}}{F_i}\right)$$

Where: E: total emissions use in a sector;

A: overall sectoral activity (vkm);

$A_i/A=S_i$: sectoral structure (by service, mode, vehicle class and powertrain group);

$F_i/A_i = I_i$: energy intensity (by service, mode, vehicle class and powertrain group);

EF_{ij}: emission factor per unit of energy for the energy carrier or fuel j used in the service, mode, vehicle class and powertrain group i.

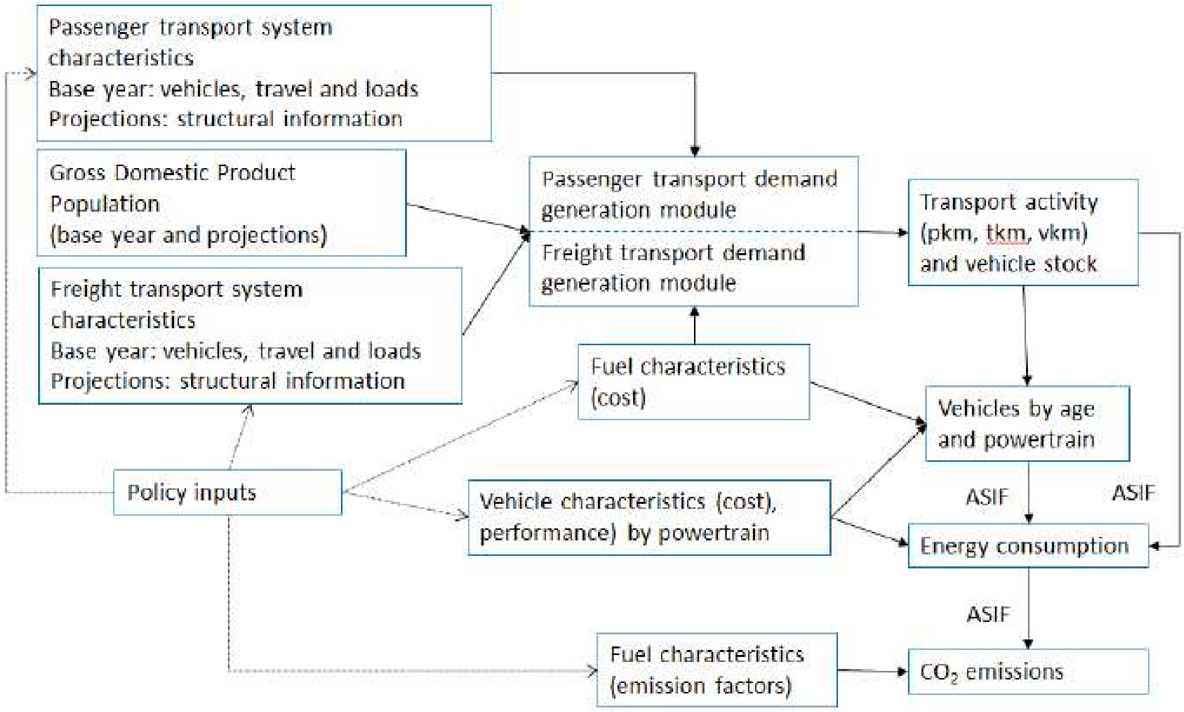

Figure 2: A synthetic description of the calculation flow (UNECE, 2013[2])

The second step of ForFITS is to change the midterm and long-term political attitude to create more comparable scenarios. This comparison can help the decision makers to choose the most suitable strategy for reaching their targets and they can also realise the effects and consequences of their present decisions. These future perspectives (of passenger kilometres, ton kilometres, energy use, CO_2 emission) can be input data of long-term external costs (for example in cost-benefit analysis's). And if politicians build in these costs into the specific transport taxes and fees it will change the share of public transport and we will be able simulate it as well.

Publications by the author related to the thesis: (Andrejszki et al., 2014b), (Andrejszki and Török, 2014a), (Andrejszki et al., 2014c), (Mészáros and Andrejszki, 2014)

[2] UNECE: ForFITS - User Manual

4. I made a research based on stated preference method and I identified the utility function of transport from the results.

First, I had to define the factors that must be considered in the transport utility function. I decided to have five factors in the model: travel time, travel cost, comfort, safety and the environmental effects. The parameters of the chosen factors were identified by the questionnaire of stated preference method. After the combinatorial optimization, I created 20 questions to estimate the individual preferences. 459 people filled out the online questionnaire. I could show that they could prescind between the transport devices they used and the abstract transport factors. I also examined the correlation between the five factors (Table Table 1). In most of the cases there were weak and negative connection between two factors which proved that the interferences between the factors did not distort the punctuality of the utility function.

Table 1: Correlations between factors (own editing)

	Travel time	Travel cost	Comfort	Safety	Environmental
Travel time	1				
Travel cost	-0,426	1			
Comfort	-0,140	-0,213	1		
Safety	-0,216	-0,398	-0,206	1	
Environmental	-0,218	-0,247	-0,222	-0,150	1

From the individual preferences, I defined the parameters of the linear utility function of the transport system. The results can be seen in Equation (**5**.

(5) $$U = 0,217 * X_1 + 0,405 * X_2 + 0,130 * X_3 + 0,134 * X_4 + 0,114 * X_5$$

where: U → the applied utility function;

X_1 → value of travel time factor;

X_2 → value of travel cost factor;

X_3 → value of comfort factor;

X_4 → value of safety factor;

X_5 → value of environmental factor.

I validated the utility function made decision simulation by comparing it with a probability model. The scheme of the validation is in Figure Figure 3.

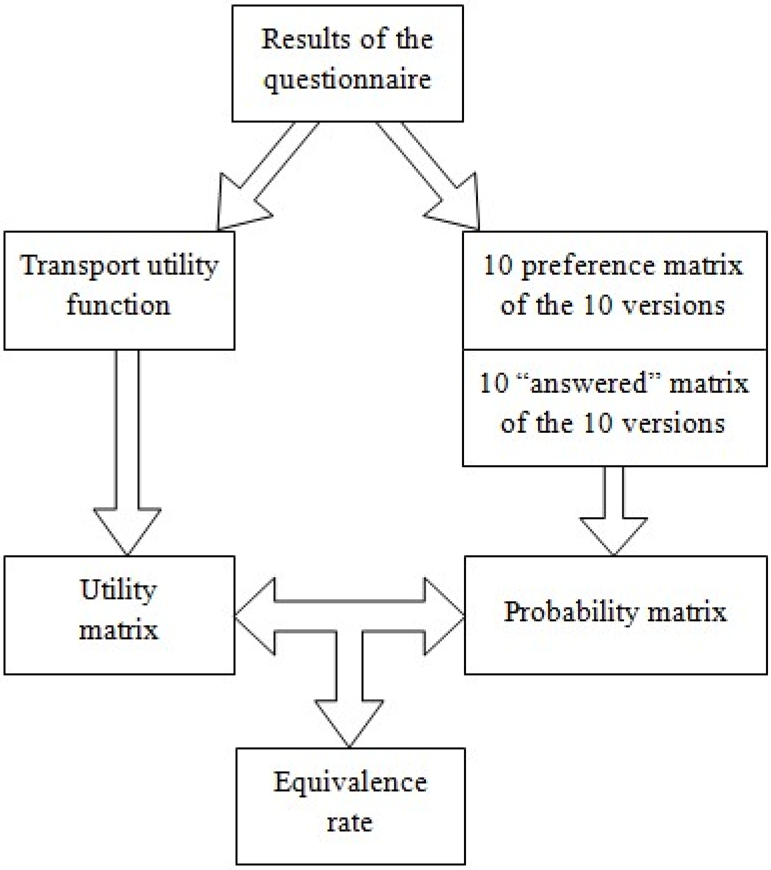

Figure 3: The process of validation (own editing)

Publications by the author related to the thesis: (Andrejszki et al., 2015), (Andrejszki et al., 2016)

5. I created a method that could calculate transport modal share data from transport utility function to help decision makers.

If the transport utility function is known, it is possible to assign values to each transport service. These values can be compared in a closed system. So, the next step of the research was to evaluate the transport services in the same scale that we used during the analysis of the questionnaire but now we can interpret the discrete values (1, 2 and 3) in a continuous scale. In some cases, evaluation can be handled in an objective way but there are cases where subjectivity makes some uncertainty in the system.

The reason why the modal share will change is that a new transport service (for example a DRT service) might have higher utility than the old one (for example the traditional bus service). In this situation, the utility of the whole public transport system will increase which means that there will be people who will change their attitude and use public transport instead of individual solutions. This estimation can be built in cost-benefit analysis's where we can calculate the demands of the newcomers, the needed capacities and the costs and incomes generated by them.

I showed the estimation of modal share change in a theoretical case study where I examined the transport system of a fictive commuter town. First, I evaluated the transport system before the introduction of the DRT service, then I put the results into the utility function (Table 2 and Table 3).

Table 2: The evaluation of interurban transport system before the project (own editing)

	Absulte time (min)	Relative time	Absolute cost (Forint)	Relative cost	Comfort	Safety	Environmental	Utility values	Modal split (%)
Car	30	3	23450	1	3	1,5	1	1,761	38,00
Bus (+public transport)	57,5	1,49	21400	1,17	1,7	1,9	1,8	1,480	28,70
Train (+public transport)	66,47	1	19080	1,37	1,3	3	2,5	1,629	33,30

Table 3: The evaluation of local transport system before the project (own editing)

	Absulte time (min)	Relative time	Absolute cost (Forint)	Relative cost	Comfort	Safety	Environmental	Utility value	Modal split (%)	Partial utility	Total utility
Car	6	3	6993	1	3	1,5	1	1,761	17,61	0,310	2,141
Bus	20	2,28	3000	2,14	1,5	1,9	1,8	2,018	22,76	0,459	
Bike	12	2,69	0	3	1	1,2	3	2,432	34,45	0,838	
Walk	45	1	0	3	1	1,6	3	2,118	25,18	0,533	

We can estimate the parameters of the planned DRT service, so Table 4 shows the change of local transport modal share after the introduction of a higher utility service (Table Table 4).

Table 4: The evaluation of local transport system with DRT service (own editing)

	Absulte time (min)	Relative time	Absolute cost (Forint)	Relative cost	Comfort	Safety	Environmental	Utility value	Modal split (%)	Partial utility	Total utility
Car	6	3	6993	1	3	1,5	1	1,761	16,66	0,293	2,194
Bus	10	2,79	4000	1,86	2,7	2,1	2,2	2,241	26,93	0,604	
Bike	12	2,69	0	3	1	1,2	3	2,432	32,59	0,793	
Walk	45	1	0	3	1	1,6	3	2,118	23,82	0,505	

The utility of the whole local transport system increases (because of DRT service) which will have effects on interurban transport also. Commuting will be more attractive because it will be easier to reach the fictive train and bus station. This change is shown in Table Table 5. The results can be handled easily; they can be put in cost-benefit analysis's and input data are accessible.

Table 5: The effect of DRT service for the interurban transport system (own editing)

	Old utility value	**New utility value**	**Old modal split (%)**	**New modal split (%)**
Car	1,761	1,761	38,00	37,08
Bus (+public transport)	1,480	1,517	28,70	29,07
Train (+public transport)	1,629	1,670	33,30	33,85

Publications by the author related to the thesis: (Andrejszki et al., 2014a)

To sum up, the researches showed that DRT systems can be an effective way to make our World, our city, our transport system more sustainable. I created a pricing system that can help operators and passengers to be more satisfied with flexible services. I created a method based on simple questionnaires that can help to estimate the transport utility function therefore the change of modal share caused by a new transport service. This method can be adapted in small towns (for example commuter cities) where DRT services might generate benefits against traditional transport systems. In cost-benefit analysis's we can numerically use these results to make these benefits comparable financially with the investment and the operational costs.

4.2. EXPEDIENCE OF NEW SCIENTIFIC RESULTS, POSSIBILITY OF FURTHER RESEARCHES

I created new methods that were proven by the examination of the theoretical basis, simulations and theoretical case studies. To make these methods applicable it is needed to have specialized pilot projects in optimal environment (for example in smaller commuter cities) to examine the real utility of an adaptable DRT service. Although the law of passenger transport services in Hungary (2012. XLI. tv.) identifies (and supports) how to apply DRT services, in Hungary we do not have the "cultural basis" for being open-minded: decision makers and local governments do not take the risk of introducing an unknown transport service that might not be used easily by the people. Local governments should pay more attention to public consultation to reduce this risk.

The utility function that I calculated was based on questionnaire that was not representative because of having much less elderly people involved. In the future, my aim is to make representative research in an environment that is optimally demarcated. From those result I will be able to identify and validate the specialized local transport utility function.

Beyond DRT services there are other sustainable services which would be worth to adapt in Hungary but the adaptation has cultural (and sometimes legal) barriers. Another way of further development can be to adapt the shown methods for these kinds of services too. My aim is to create and support creating studies and researches that can help decision makers to choose sustainable transport systems because of their quantifiable social benefits.

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