Complex analysis of urban bicycle transport systems, using innovative methods

Abstract

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1 Overview

The structure of my PhD dissertation is as follows. Chapter 1 is the Introduction, which justifies the choice of the topic and describes the objectives of the research. Each further chapter is dedicated to a different significant problem. Each chapter includes a literature review, the presentation of the data and methods, which are either taken over from other studies or have been created by me. Results and conclusions are also discussed in detail. Finally, each chapter is concluded by a list of my novel scientific results in the given topic.

The problem of the perceived safety of the bicycle infrastructure has interested me for long. As a contributor to an international R&D project, I had the opportunity to comply a detailed questionnaire and conduct a comprehensive survey in this field. The data obtained from this survey have been analyzed in depth, and conclusions have been drawn in my PhD research project (Chapter 2).

Owing to the spread of Public Bike Sharing (PBS) systems, it has gained primary importance to understand the differences between the different systems. However, the comparison of different PBS systems is difficult based on the literature, as a comprehensive database is missing. Furthermore, only incomplete methodologies have been published or are being set up, which focus solely on specific areas. Consequently, no comprehensive, open-access and easy-to-use methodology is available that could facilitate the decision making process for planners, experts and decision makers. Based on existing methodologies, I created an innovative and comprehensive framework for categorizing and analyzing PBS schemes in my doctoral research.

The first problem was the total lack of a transparent, open-access database of publicly available data. Consequently, the first task was to collect and organize the necessary data. Based on these data, the existing PBS systems can be clustered, and the typical models corresponding to these groups can be identified. Not all parameters were used for cluster analysis, only a subset of these and a set of derived values calculated from the parameters. Results were visualized with graphs. Therefore, a general methodology was created to determine the type of a planned or existing PBS system based on some parameters (Chapter 3).

The next step of my research was to establish an evaluation framework containing absolute scales for comparing different PBS systems. A separate benchmark was created for users and for operators. As the weighing of criteria is a key element of the system, the weights were validated by the Analytic Hierarchy Process (AHP) method, using a questionnaire prepared by me (Chapter 4).

Chapter 5 concludes the dissertation by summarizing novel results, highlighting the applicability of the methods described here and adding further directions of research.
2 Actuality of the research

According to the 2013 UN forecast, the population of the world, which is now 7.2 billion, will reach 8.1 billion by 2025, and 9.6 by 2050. The largest boom is expected in the developing regions, while the population of developed countries is expected to change minimally. Urbanization is forecasted to strengthen, as a result of which the number of people living in cities is expected to grow from 3.3 billion to 6.4 billion. This means, the whole predicted population growth is to be realized in cities, while people living in rural areas will continue to move into cities (United Nations; Department of Economic and Social Affairs; Population Division, 2013). This 2013 prognosis has been updated twice, and in both cases the growth rate was estimated to be higher (United Nations, 2015; United Nations; Department of Economic and Social Affairs; Population Division, 2019).

The proportion of city dwellers differs according to region. In Europe, 73.4% of people live in urban settings, while this value might reach 80% by 2050 (Buzási and Csete, 2015). Geoffrey West illustrates this change from a different perspective in his presentation (West, 2011): “Every week for the foreseeable future, until 2050, every week more than a million people are being added to our cities”. An important prerequisite for providing a high level transportation system in a city is a quality change in urban development, which might lead to a rise in the living standards (Kampf, Gašparík and Kudláčková, 2012).

As a consequence of the above, cities are to determine the lifestyles of future generations. Citizens have high transport demands; therefore, the forecasting and modelling of transport in cities is of primary importance. Owing to the growth of cities, the problem of urban mobility is growing exponentially. However, as the inventor of the Buzzcar system, Robin Chase (Schwartz, 2013) has quoted in his lectures several times the words of Professor Banny Banerjee, Stanford University: “exponential problems cannot be solved with linear solutions”. Consequently, new models must be created to satisfy the demands.

This means, the growing problems cannot be solved by the classic engineering methods. The requirement for sustainable transport has caused fundamental changes in the practice of transportation planning: a paradigm shift has been witnessed from the “predict & provide” perspective to the “aim & manage” approach. Sustainable transportation investments and solutions are not only beneficial for economic and environmental fields, but also have positive financial effects (Mátrai, Kerényi and Juhász, 2013; Juhász and Mátrai, 2014; Juhász, Kerényi and Mátrai, 2014).

In the past decade, the car-centered perspective has changed considerably, primarily due to the wide spread of new planning approaches, such as the Sustainable Urban Mobility Planning (SUMP). This human-centered approach aids to find the optimal combination of different transport modes (Rupprecht Consult, 2019).

This new approach brings shared spaces into focus, as these areas do not only provide surfaces for transport, but may also form liveable public spaces. However, it seems that shared spaces and the “liberal” approach connected to them work only in countries with high transport morale and the participants of transportation respect each other (Mátrai, Tóth and Cruz, 2020).
The management and development of transport systems must always stem from the knowledge of transport demands. To collect such information, different types of surveys can be conducted (Cre, Mátrai and Wolek, 2013). The effects of international trends (travelling habits of young generations, aging society, the continuous development of information and communication technologies, the paradigm shift of transport planning and management) are also witnessed in Budapest (Juhász, Kerényi and Mátrai, 2014).

Various urban transport models can aid well-founded decision making in the future. However, the number of studies on the integration of non-motorized transport modes into such models still remains low. Budapest is at the cutting edge of the development of a strategic transport model (Szabó, Halms and Mátrai, 2018). The bicycle layer has been considerably developed in the Budapest model in the past few years (Mátrai et al., 2016). The model sets up 7 different infrastructure categories with respect to how much they are bikeable (Mátrai, Ábel and Kerényi, 2015).

Cycling is beneficial for the economy, reduces environmental burden, allows for a healthier lifestyle for citizens and improves the conditions of public transport (Eueliton et al., 2016). Bicycle use has established links between social, cultural and economic spheres (ITF, 2013). Cycling is often mentioned (Médard de Chardon, 2019) as a positive initiative for solving the problems of global sustainability and western health issues such as obesity, and also for handling social inequities. Additionally, cycling is cheap and ensure from door to door mobility for distances that are typical for intracity travels, i.e. around 5 km (Veryard and Perkins, 2018).

Traffic surveys help to explore the travellers’ demands and reactions to changes of transport conditions (Mátrai and Glász, 2018). To carry out a traffic count is the easiest way to record travel demands. However, the knowledge of the quantity of traffic is not sufficient for understanding the deeper connections and the causal relationships of passenger transport. Interviews, especially household surveys, are the primary tools for obtaining information of urban travel changes. Motivations for mode and route choice can be detected by stated preference (SP) and revealed preference (RP) methods (Berki, 2008), (Bocz, Kisgyörgy and Vasvári, 2017).

Besides other factors, two decisive factors at play for the better integration of bicycles and motor vehicles must be mentioned: (i) road safety and (ii) safe bicycle infrastructure (Castro, Barbosa and Oliveira, 2013). According to Berki (Berki, 2008) and Buehler and his colleagues (Buehler and Pucher, 2012), (Pucher and Buehler, 2017), one of the most important factors for the spread of cycling is the perceived safety of cyclists. They also found that the higher level the separation between motor vehicles and bicycles is, the higher safety is perceived by cyclists.

At the same time, according to DiGioia et al., few studies are available that compare the accident statistics of a given route before and after different interventions (DiGioia et al., 2017). This means, the above claims can hardly be underpinned by facts. However, it must be taken into consideration that Monsere et al. claim that perceived safety and the users’ perception is of higher importance for the decision making of cyclists than the objectively measured risk of accidents (Monsere, McNeil and Dill, 2013).
According to the definition of the European Cyclist Federation, a Bike Sharing System (BSS) is a bike rental scheme, in which bicycles can be rented for short times, even for one-way trips. The parts of the system are located in public areas, form a network and offer possibilities for a variety of users (ECF, 2012).

In general, the aim of the deployment of PBS systems is to increase cycling, to widen the transport possibilities, to reduce air pollution and to decrease traffic jams (Midgley, 2011). By making bicycles available, which is the fundamental policy of PBS schemes, people have access to bikes without the costs and responsibilities of a bicycle owner (Shaheen, Guzman and Zhang, 2010). As PBS systems are spreading, it is crucial to understand and explore these systems.

The main idea behind the benchmarking part of my dissertation is connected to the Urban Mobility Index, developed by the Arthur D. Little Company (Van Audenhove et al., 2014). The first article on this topic by Arthur D. Little was published in 2010, with the title Future of Urban Mobility. The company described their method of calculating the Urban Mobility Index, which evaluates the performance and maturity of traffic and mobility in cities. From research perspectives, the great advantage of this index was that the calculation could be replicated, as all weighing and scoring algorithms were transparently described. Since then, the company has signed a strategic contract with the UITP (International Association of Public Transport - L’Union internationale des transports publics) and they have already published a refined version of the index. The number of examined cities all over the world has reached 84. The number of evaluation criteria has risen to 19 from 11. Despite that the index is easy to calculate and the algorithm is public, the calculation process has problems. Without all the necessary data of the evaluated cities, the process can be reproduced, but might give false results.

The European Conference of Ministers of Transport (ECMT, 2004) suggests various analytical methods to evaluate transport investments: MCA, value analysis (VA), cost-benefit analysis (CBA), tariff analysis. Different evaluation methods are used in almost all segments of the European Union. Having reviewed various MCA (Multi-criteria Analysis) methodologies, I have chosen the most suitable one.

Comparative methods like the MCA evaluate alternatives, while other methods compare one solution to an absolute value. The most often applied comparative method is the MCA or benchmarking (Gyarmati, 2003; Rapcsák, 2007; Kukadapwar and Parbat, 2016). All MCA methodologies can be put into one of the three major categories: general comparative, compensatory and classificatory (Magyar et al., 2000; Mándoki, 2005). Several methods exist to determine the weighs in these methodologies, but as Oliveira points out, all methods rely on the decision-maker’s judgements (Oliveira, 2010).
3 Identified research gaps and aims

During a comprehensive review of the international literature, the following gaps were identified.

- Only few studies are available on the topic of the relationship between the elements of bicycle infrastructure and the perceived safety of cyclists.
- Only few studies reveal the different customs of cyclists as a heterogeneous group and analyze the effects of such differences.
- In Hungary, only few comprehensive surveys based on questionnaires have been conducted on the behaviour of cyclists.
- No international public database is available on the characteristics of PBS systems.
- Different business models have been identified for PBS schemes. However, the connections between the schemes and the business models have not been determined satisfactorily.
- The method of cluster analysis has not been applied to categorize transport services.
- No methodology for the systematic categorization of PBS systems was available.
- There was no transparent, reproducible and widely applicable methodology for the comparison of PBS schemes.
- The perspectives of different players have not been described and their effects have not been explored.

When choosing my research topic, I proceeded from a broader perspective to a narrower one (Figure 1). Within the transport system, I identified the urban transport system as a highly important subsystem. Within urban transport, I focused on active transport modes, especially on cycling. The cycling subsystem, similarly to any other transport systems, has three main pillars: people, infrastructure and vehicle. These pillars should not only be examined on their own, but also the interactions and system dynamics between them.
Based on the gaps in the literature, I found and created methods that can aid transport practitioners and decision makers. Relying on the applied methods, I made claims that can be used as starting points for the designing process and support the complex decision making processes. An important aim of my research was to create scientific devices to help the providers of the cycling infrastructure to learn about the characteristics and demands of the user side (i.e. cyclists, citizens). Consequently, I set the following research aims:

- to explore the connections between the perceived safety of cyclists and the cycling infrastructure;
- to create an open and open-access international PBS scheme database;
- to create the methodology for categorizing PBS systems;
- to carry out a comparative analysis of PBS schemes;
- to reveal the connections between the perspectives of the users and the operators of PBS systems;
- to validate the weighing used in the comparative analysis of PBS schemes.
4 Applied methods

In my PhD research, first of all I analyzed the question of the perceived safety of various elements of cycling infrastructure. Secondly, I concentrated on PBS systems, as an exponentially developing transport option. My main focus was the categorization and comparison of different PBS schemes. The methods and data used in the course of the research are shown in Figure 2.

![Diagram showing the methods and data of my PhD research](image)

Figure 2. Methods and data of my PhD research

In 2016, the BKK (Centre for Budapest Transport) ordered a household survey, which consisted of two parts. Both parts were conducted with the CAPI (computer assisted personal interviewing) method. The first part of the survey was a stated preference experiment, in which the interviewees had to choose among different modes of transport in various situations ($n = 3507$). The second part of the survey was a simple questionnaire about cycling behaviour and preferences ($n = 1511$). I worked in this project as an external expert for the completion of the survey and the wording of questions (Szabó, Halmos and Mátrai, 2018). In my doctoral research, I used the data collected by the second part of the survey.

The first step was to depict data with graphs. With the help of these graphs, 10 hypotheses were set up. Then, various descriptive statistics were calculated. As most of the data contained categorical variables, 6 further hypotheses were evaluated with the chi-square test. The categorization method created in this dissertation contains 8 steps.

The advantages of the MCA methods include easy calculability and wide applicability (Esztergár-Kiss and Csiszár, 2016). Based on the review of the literature, I opted for the compensatory multi-criteria analysis. In the first round, I determined weights based on my expert experience, then I applied the AHP method with the help of a questionnaire (Saaty, 2008). As the perspectives of the users and the operators are different, two scales were created. The points for a given scheme for a given subcriterion were calculated with linear interpolation, taking the limits into consideration (the worst and the best value).

The main steps of my research are shown in Figure 3.
I prepared an online questionnaire to validate the weights for the user perspectives, which was evaluated with the AHP method. This method allows for revealing the subjective opinion of experts (Saaty, 2008). The AHP method also allows for some inconsistency, as in reality our decisions are not entirely consistent either. Proportion scales are deduced from the main eigenvectors, while the consistency index is deduced from the main eigenvalue.

As the exact points are not really important, I used rank correlation. This statistical method examines the relationship between different variables based on an arbitrary monotonous function. In practice, two important rank correlation coefficients are used: Spearman’s $\rho$ (or $r_8$) and Kendall’s $\tau$. In general, rank correlation coefficients are not very sensitive to outliers.

5 Novel scientific results

**Thesis 1**

*I surveyed the perceived safety of cyclists in order to enhance the understanding of cyclist’s demands for the operator and planner of the cycling infrastructure. Based on my evaluation of questionnaire data, I proved that the perceived safety of cyclists plays a crucial role in increasing the proportion of cycling in urban transport. I also found that the perceived safety of the group of young males significantly differs from that of the whole surveyed population. I concluded that comfort and safety highly correlate.*

*Own publications related to Thesis 1:* (Mátrai, Tóth and Cruz, 2020); (Rudolph and Mátrai, 2018); (Szabó, Halmos and Mátrai, 2018); (Mátrai et al., 2016)
I evaluated and analyzed the data obtained from the household survey on cycling habits with statistical methods. Based on the results, I formulated Thesis 1 concerning the perceived safety of cyclists.

The respondents ranked the following factors according to their importance in route choice (1 = the most important one, 4 = the least important one). According to the results, the most important factor is perceived safety (Figure 4).

![Figure 4. Factors influencing route choice ranked according to importance (n = 672)](image)

Those surveyed were shown 9 different cycling infrastructures illustrated by images, and the respondents evaluated them according to comfort and safety (-3 = very bad, 0 = neutral, +3 = good). According to my hypothesis, the comfort and safety of a given cycling infrastructure correlate. I used the chi-square method to prove this. According to my null hypothesis, there is no correlation between comfort and perceived safety in any of the examined cycling infrastructures. As each $p$-value proved to be lower (Table 1) than the applied significance threshold ($d = 0.05$), all null hypotheses were discarded. Consequently, comfort and safety are correlated. Furthermore, it is highly probable that comfort as a complex notion includes safety issues.

**Table 1. Results of the chi-square test related to the correlation of comfort and safety (n = 672)**

<table>
<thead>
<tr>
<th>Cycling infrastructure</th>
<th>F value</th>
<th>df</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential street</td>
<td>1733.047</td>
<td>36</td>
<td>&lt; 0.000</td>
</tr>
<tr>
<td>2×1 lane road with medium traffic</td>
<td>1585.376</td>
<td>36</td>
<td>&lt; 0.000</td>
</tr>
<tr>
<td>Multilane road with high traffic</td>
<td>1435.057</td>
<td>36</td>
<td>&lt; 0.000</td>
</tr>
<tr>
<td>One way street to be used in both directions for cyclists</td>
<td>1431.786</td>
<td>36</td>
<td>&lt; 0.000</td>
</tr>
<tr>
<td>Bus lane to be used by cyclists as well</td>
<td>1434.380</td>
<td>36</td>
<td>&lt; 0.000</td>
</tr>
<tr>
<td>Mutual path for cyclists and pedestrians</td>
<td>1477.537</td>
<td>36</td>
<td>&lt; 0.000</td>
</tr>
<tr>
<td>Bicycle lane</td>
<td>1492.918</td>
<td>36</td>
<td>&lt; 0.000</td>
</tr>
<tr>
<td>Separated walking and cycle path</td>
<td>1920.106</td>
<td>36</td>
<td>&lt; 0.000</td>
</tr>
<tr>
<td>Dedicated cycle path</td>
<td>2443.596</td>
<td>36</td>
<td>&lt; 0.000</td>
</tr>
</tbody>
</table>

In order to prove, that cycling is not a homogeneous group, I created a subgroup of young male cyclists. My next hypothesis was that young male cyclists sense certain elements of the
cycling infrastructure differently from the average. In order to prove that hypothesis, I used the chi-square test. My null hypothesis was that there is no correlation between the perceived safety parameters of the group of young males and of the basic population (i.e. they are not correlated).

Concerning different infrastructure types, the $p$-value (Table 2) proved to be higher than the applied significance threshold ($d = 0.05$). Thus, in these cases the null hypothesis cannot be discarded. This means that young male cyclists sense the safety of the Multilane road with high traffic, the Mutual path for cyclists and pedestrians and the Dedicated cycle path differently from other cyclists. I cannot support the nature of the difference with statistical data, due to the lack of related questions and exact data, however it can be assumed, that young male cyclists have a higher willingness to take risks, so they evaluate these infrastructure types safer.

Table 2. The results of the chi-square test related to the correlation of young male cyclists and perceived safety of different infrastructure types ($n = 672$)

<table>
<thead>
<tr>
<th>Cycling infrastructure</th>
<th>F  value</th>
<th>df</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential street</td>
<td>15.089</td>
<td>6</td>
<td>0.020</td>
</tr>
<tr>
<td>2×1 lane road with medium traffic</td>
<td>14.541</td>
<td>6</td>
<td>0.024</td>
</tr>
<tr>
<td>Multilane road with high traffic</td>
<td>7.137</td>
<td>6</td>
<td>0.308</td>
</tr>
<tr>
<td>One way street to be used in both directions for cyclists</td>
<td>23.411</td>
<td>6</td>
<td>0.001</td>
</tr>
<tr>
<td>Bus lane to be used by cyclists as well</td>
<td>16.103</td>
<td>6</td>
<td>0.013</td>
</tr>
<tr>
<td>Mutual path for cyclists and pedestrians</td>
<td>8.335</td>
<td>6</td>
<td>0.215</td>
</tr>
<tr>
<td>Bicycle lane</td>
<td>16.768</td>
<td>6</td>
<td>0.010</td>
</tr>
<tr>
<td>Separated walking and cycle path</td>
<td>20.702</td>
<td>6</td>
<td>0.002</td>
</tr>
<tr>
<td>Dedicated cycle path</td>
<td>8.502</td>
<td>6</td>
<td>0.204</td>
</tr>
</tbody>
</table>

**Thesis 2**

*I have created an open-access database for the PBS schemes of the world, in order to categorize these systems by various parameters, containing 64 systems and 73 parameters for each one. I created a method consisting of 8 steps including data collection, cluster analysis, statistical tests, regression, internal and external cluster validation techniques.*

Own publications related to Thesis 2: (Mátrai and Tóth, 2020a); (Soltani, Mátrai, Camporeale, et al., 2019); (Soltani, Mátrai, Allan, et al., 2019); (Mátrai, 2019); (Mátrai and Tóth, 2016a); (Mátrai and Tóth, 2016b); (Mátrai and Tóth, 2016c); (Tóth and Mátrai, 2015)

I have created a detailed database, which contains 64 PBS schemes and 73 parameters. I have created a method of 8 steps to categorize PBS systems, which is made up of statistical calculations and a comprehensive cluster analysis as well (Figure 5). The first step was data collection, which was followed by data analysis. The next step was to carry out the first cluster analysis based on my professional opinion. The fourth step is to run statistical tests and carry out regression analysis in order to choose the parameters for the second cluster analysis. This
is followed by the second cluster analysis based on the selected parameters. Finally, inner and outer cluster validation techniques are applied.

### Figure 5. Flowchart of the proposed cluster analysis method

<table>
<thead>
<tr>
<th>Data collection</th>
<th>from public databases</th>
<th>from the systems’ website</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data analysis</td>
<td>Clusterability</td>
<td></td>
</tr>
<tr>
<td>Cluster analysis I.</td>
<td>based on my professional opinion</td>
<td></td>
</tr>
<tr>
<td>Univariate statistical tests</td>
<td>Chi-Square test</td>
<td>One way ANOVA test</td>
</tr>
<tr>
<td>Multivariate regression</td>
<td>Manual backward method</td>
<td></td>
</tr>
<tr>
<td>Cluster analysis II.</td>
<td>based on selected parameters</td>
<td></td>
</tr>
<tr>
<td>Internal cluster validation</td>
<td>Dunn index</td>
<td>Average silhouette distance</td>
</tr>
<tr>
<td>External cluster validation</td>
<td>Defining “Other” cluster</td>
<td></td>
</tr>
</tbody>
</table>

Three scenarios were compared during the analysis of the results, each corresponding to different parameters:

- Scenario 1: full data set (all recorded 73 parameters);
- Scenario 2: parameters selected by statistical tests and multinomial regression;
- Scenario 3: solely the Operator and Owner parameters.

### Thesis 3

I set up 3 major categories based on the properties Operator and Owner: (i) fully public schemes; (ii) fully private schemes; (iii) mixed schemes. Using the methodology described above, I concluded that approximately 50% of PBS schemes in my database can be put into one of the above major categories unambiguously.

Own publications related to Thesis 3: (Mátrai and Tóth, 2020a); (Mátrai and Tóth, 2020b); (Soltani, Mátrai, Camporeale, et al., 2019); (Soltani, Mátrai, Allan, et al., 2019); (Mátrai, 2019)

I carried out the steps of my categorizing method in 2 iterations. After the evaluation of the results (Figure 6), I formulated Thesis 3 about the categorization of PBS schemes.
The general characteristics of the major clusters are as follows.

- **Cluster 1 – Fully public schemes**: The owner and the operator of the system are both public companies. The owner is generally the city or one of the city’s companies. The operator can be the same company or a different one, established for this particular purpose. Income is realized directly from the fees, but generally requires subsidies. The aim of such systems is usually offering an extra transport possibility, or influencing or changing the transportation habits of citizens, instead of making a profit. Typical examples include the B-cycle systems of the USA.

- **Cluster 2 – Fully private schemes**: Both the owner and the operator of the system are private companies, generally the same profit-oriented company. Income is realized from fees and advertisements. The main aim is to gain profit; therefore, operation is designed in a more efficient way. Additionally, certain restrictions might be applied to the network or the users. Typical examples include the schemes owned and operated by NextBike.

- **Cluster 3 – Mixed schemes**: Generally, the owner of the system is a public organization (usually a city or a transport provider company), while the operator is a private company. The owner's aim is generally to offer a wider range of transport possibilities for citizens, while a private company provides the service. According to the income sources, there are basically two business models available for the private company. In both cases, user fees are collected by the owner, i.e. the financial risk of usage is that of the owner. In the first business model, the operator receives a service fee (availability payment) based on the Service-level Agreement (SLA). In the second business model, the operator is allowed to use various advertising spaces in and around the city to cover the expenses of operation. The two business models are not different enough for my method to be assigned to different clusters based on the parameters used. Typical examples include the MOL-Bubi (Subtype 1) and the Velib (Subtype 2).
Cluster 4 – Other schemes: There are several schemes that an unsupervised algorithm would assign to one of the above clusters, but based on an expert definition, they do not fit into the assigned cluster. The reasons are usually difficult to identify. An example is when a public company devises a profit-oriented scheme, or when a private company acts in a similar manner to public companies. According to the characteristics of the political structure, this problem is outstanding for the categorization of Chinese schemes.

Thesis 4

*I conducted a comparative analysis of PBS systems in order to evaluate these from the perspective of both users and operators based on a uniform methodology. Based on the collected data and the benchmarking method created by me, I proved that the PBS systems that are regarded as outstanding from a user perspective are generally considered to be outstanding from an operator perspective as well.*

Own publications related to Thesis 4: (Mátrai, 2016); (Mátrai, Mándoki and Tóth, 2016)

I extended the database with additional derived parameters. I created a multi-criteria evaluation frame in order to compare PBS schemes from the user and operator perspectives. The method was applied to the schemes in the database, and the results were analyzed. I formulated Thesis 4 on the comparison of PBS systems based on the results.

For the user perspective, I used 5 main criteria and 21 subcriteria. Based on my experience the main criteria were weighed equally, i.e. 0.2 each.

- **UCO** – Coverage. This main criterion depicts how the PBS scheme covers the city and the agglomeration area. It unifies geographical and demographic coverage.
- **UAF** – Affordability. This main criterion shows how affordable the usage of the system is. It uses values determined from the average income of citizens and the public transport fees.
- **UAC** – Accessibility. This main criterion signals how easy it is to access the system. It uses subcriteria that inform about the operating hours and the process of registration.
- **UIT** – Integration. This main criterion indicates how much the PBS scheme is integrated into the urban transport system.
- **UIN** – Innovation. As innovation is essential for fourth generation systems, this criterion shows how many innovative elements a given PBS scheme has.
The other set of criteria summed up the factors important for the operator of the PBS scheme. I described the operator’s perspective using 4 main criteria, and 17 subcriteria. The four main criteria were assigned the same weight (i.e. 0.25).

- **OCO** – Coverage. This main criterion depicts how the PBS scheme covers the city and the agglomeration area. It unifies geographical and demographic coverage. Subcriteria are the same as for the user criteria.

- **OAF** – Affordability. This main criterion shows how affordable the usage of the system is. It uses values determined from the average income of citizens and the public transport fees. Subcriteria are the same as for the user criteria.

- **OOP** – Options. This main criterion informs about the potential of the system. It combines demographic data with general information on the city.

- **OCX** – Complexity. This main criterion describes how complex the given scheme is from the operator’s point of view, how difficult it is to manage. Parameters that are innovative from user perspective increase the complexity of the system on the operator side, that is why they appear here as well, but with opposite scale.
The significance of the correlation between ranks was determined by both Spearman’s rho and Kendall’s tau coefficients. Both coefficients signalled strong correlation ($\rho = 0.861856$ and $\tau = 0.697357$). As the $p$-value is < 0.000, the null hypothesis was discarded, i.e. the correlation proved to be significant in both cases.

Figure 8. Operator criteria for PBS schemes

Figure 9. The comparison of the ranking by user and operator perspective
Thesis 5

I surveyed the opinion of experts concerning the PBS schemes with a questionnaire prepared by me, to validate weights. Based on the data obtained and the AHP method, I determined the weights for the multi-criterion analysis from user perspective. I repeated the benchmarking evaluation with the new weights. The calculations proved that the results differ from the earlier results to a minimal degree.

Own publications related to Thesis 5: (Mátrai, 2016); (Mátrai, Mándoki and Tóth, 2016)

I have complied a questionnaire based on the AHP method to determine the weights for the analysis. I evaluated the responses, filtered consistent respondents, and I determined the weights. I rerun the comparative analysis with the new weights. Based on the results, I formulated my Thesis 5 about the AHP method and the weights applied in the MCA process.

Using the described methods, I calculated the consistency ratio (CR) of respondents. The ranked results are given in Figure 10. Out of the 23 complete responses, 10 could be regarded as consistent enough, as the CR value for these is less than 25%.

![Figure 10. Consistency ratio of respondents, ordered](image)

Using the 10 acceptable inconsistent samples, I determined the average weight ratios in a way that their sum should be 100%. The weights determined by the AHP method (AHP) and the weights determined by me earlier (MT) are depicted in Figure 11. In the case of the questionnaires, I also gave the standard deviation.
The next question was whether there is a correlation between the order of the systems determined by me and by the AHP method. As the above figure shows, the difference is minimal in the whole scale. I determined the significance of correlation both by Spearman’s rho and by Kendall’s tau coefficients. Both coefficients ($\rho = 0.980197$ and $\tau = 0.886616$) show strong correlation. As the $p$-value is $< 0.000$, the null hypothesis was dropped. Consequently, the correlation was proved to be significant in both cases.
6 Practical applicability

My aim was to create results and new engineering methods that can be used in practice. Civil engineers can use my results concerning the perceived safety of cycling infrastructure. On the one hand, my results can be included in course materials at the university; on the other hand, they can be used in the decision making process about cycling infrastructure investments.

The categorization process of PBS schemes can aid the planners of new systems and the developers of existing systems. The benchmarking method for PBS systems that I created is a generally applicable methodology, which can evaluate any existing or new system from the perspective of the users or the operators. Furthermore, this framework can be used to compare the schemes in the world.

Owing to the fact that active transport modes gain more and more importance, it is of crucial significance that decisions should be made based on a thorough and well-founded decision-making process. For this, it is indispensable to create methodologies that are easy to use and the results of which can be depicted easily. For this reason, these methods can be applied by those cities and companies that do not have enough capacity for a comprehensive analysis.

7 Further research directions

Several problems have emerged during my doctoral research that are worth exploring. Concerning the safety of the elements of the cycling infrastructure, it would be important to carry out ex-post analyses in order to be able to determine the objective safety of these elements. The data to be used for such an analysis includes traffic data, accident statistics and the data of infrastructural investments.

Instead of the cluster analysis applied in my categorization methodology, other hierarchical methods could also be used. The database created in this research can be extended with additional parameters, especially concerning the aim and usage data of systems. A limitation of the current database is that it does not handle dockless systems. It could be examined whether such systems form a separate cluster, or that category needs to be broken down to subclusters.

The comparative analysis of PBS schemes has been fully published; therefore, it can be hoped that new systems will be included in the database in the future. The AHP weight calculations could be carried out for the operator’s perspectives as well. However, this would require consulting several operational experts.

In order to create a complete, comprehensive framework for analyzing PBS systems, the missing modules include: the updating of various macroscopic models for impact analysis; amendment of the cost-benefit analysis with the benefits of PBS schemes; system dynamics models could aid the analysis of the operation of PBS systems.
8 References


