ANALYSIS OF GAME THEORY BASED APPLICATIONS ON INFRASTRUCTURE COST ALLOCATION IN HUNGARY

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1. INTRODUCTION

In the past years the integration process of the European Union has speeded up considerably, which brought up more and more problems to be solved. Among these problems, one of the most relevant areas is transportation, especially road transportation and related issues. Increasing traffic volumes, parallel deteriorating traffic conditions, and the growing needs of financial resources in the road sector enforce several changes in the European as well as in the national transport policies. It is necessary to create an efficient, fair and equal road charging system. The importance of road charging as a policy measure is proven by volume of revenues from charging. This is great additional proceeds for the mostly scarce and lacking central budget in context of developing, operating and maintaining road infrastructure. Furthermore, road charges are accurate measures of demand management towards solving capacity, congestion and environmental problems.

The New Member States (NMS) of the EU also have to wrestle with these problems. However, the circumstances in Hungary and in Central and Eastern European Countries are significantly differing from conditions of the EU 15. This fact sets additional challenges in these countries.

Before the start of transition in 1989, Hungary lacked a developed motorway network. After the structural change from the planned to the market economy, the country played an important role in the NAS (Newly Associated States) region in the last one and a half decade regarding the private sector's involvement into financing road infrastructure development. The region's first two concession motorway projects (among a few public ones) had been realised in Hungary. Therefore, the extension of the national motorway network could be started by involving private capital. This development process resulted in various forms of road tolling regimes and toll collection on the Hungarian motorway network at the end of the 1990's. The interest of the country was to set up a unified tolling system.

In 2000, the government started the implementation of a flat-rate vignette system throughout the country; the last step in this process was taken in 2004. However, this vignette system is unable to solve the financial problems of the road sector; moreover, it causes social stress due to its unfair and inequitable attribution (favouring regular users and heavy good vehicles (HGV) contrary to casual users and passenger cars (PC), which latter produce less external costs). There are missing databases that would contain the exact and detailed yearly road infrastructure costs and revenues. In addition, regarding the former and existing charging systems, the revenues do not meet the road infrastructure costs. The prices are set up by the state considering several economic and social needs and, of course, political aspects.

The way ahead can be to apply a more efficient and fair charging system. Although these are commonly accepted and supported principles, there is no existing, uniformly accepted concept about their realisation. In recent years, a lot of research studies dealt with defining real costs of road infrastructure and allocating them to different user groups. These studies were based on expenses incurred and their characteristics.

Among other solutions, game-theoretic concepts could help in exploring and solving these problems. Nevertheless, the different applications require a reasonably thorough information collection and precise modelling. These preconditions have to be fulfilled definitely to reach the goals mentioned above.

This paper presents a way to allocate common cost of road infrastructure to different user groups in Hungary applying a game-theoretic concept. Within road transportation, this research focuses on motorways, namely motorway users: they have to pay directly for infrastructure use in Hungary. The first part of this paper introduces the history and a short evaluation of motorway development and operation in the country. This is followed by a part sorting the different game-theoretic concepts and analysing their applicability in road transportation. This article summarises the results of existing studies and research based on international scientific literature review. The next part analyses the adaptability and applicability of different concepts in Hungary's point of view. It compares and verifies the calculations of a particular application to the existing charging scheme. Last, the analysis and comparison lead to conclusions, to expected benefits of such an application and to accentuation of importance of setting up a new charging system in the future.

2. HISTORY OF PRICING REGIMES ON THE HUNGARIAN MOTORWAY NETWORK

In Hungary, generally the motorway costs and revenues do not relate very closely to each other. The reason is that the former planned economies (also in Hungary) did not approach the financing problem from expenditures of infrastructure but from revenues. The rates or prices of different state operated services (including infrastructure provision) were set up by the government. This approach still remained the same after the structural change from the planned to the market economy. Moreover, this concept determines the charging process up to now. Although for the motorway network there is a ministerial decree that revenues from motorway charges shall meet the costs of operation and maintenance, the rates for different user categories are set up by categories' revenue-generating potential. The short demonstration of historical background provides the understanding of their reasons.

In Hungary the motorway network was considerably underdeveloped before the transition. The construction of elements started in the 1960s, but only 368 km had been realised in the next 30 years. After the transition the motorway construction programme was in need of substantially speeding up, namely, the expansion of motorway network was one of the motive forces of EU integration process for Hungary.

In 1992 the new road and concession laws created the possibility of involving private capital into road infrastructure development. According to these laws the monopolistic rights of financing, building and operation of infrastructure could be transferred to private concessionaire under certain conditions included in the contract for a limited time period (Tánczos et al., 2004a).

Following the procurement notice published in September 1991, the first concession motorway construction and operation contract to M1/M15 motorways was signed in April 1993. The initial toll rates were defined in the concession contract by vehicle categories and toll plazas. Different multipliers were assigned to different vehicle categories. The passenger car category served as a basis with no multiplier (or 1,0) and then each category received a weight (i.e. a multiplier) according to the load affected on the road by vehicle falling into the category. Rates were automatically escalated without any prior consent of the Ministry according to domestic consumer price index and/or the exchange rate differential in proportion of loans raised in USD and DEM. There were discount schemes used on the motorways supporting frequent and local users.

The second concession contract related to M5 motorway was signed in 1994. Conditions were quite the same as by M1/M15 concession contract, loans were raised in FRF. There were also similar discount schemes applied to frequent and local users.

When comparing the average income / month values between Hungary and the EU, the extremely high values of Hungarian toll rates mark out (see Table 1.).

	Hungary (M1/M15)	Hungary (M5)	EU average
Toll rate for PCs	0,15 EUR/km	0,12 EUR/km	~0,07 EUR/km
Average income/month	~400 EUR	~400 EUR	~1000 EUR
Average monthly income allows to travel by PC	~2670 km	~3330 km	~14300 km

Table 1: Comparing of motorway toll rates and incomes in Hungary and in the EU in 1999 (Source: own calculations)

In the beginning of 1999, besides the two concession motorway companies there were also two other state-owned companies on M3 and M7 motorways. This meant four different types of charging regimes in Hungary that time. In 1999 the M1/M15 quite bankrupted, because revenues were insufficient due to extremely high toll rates (Tánczos et al., 2004a). The actual government decided about buying-out the concession rights and the motorways got back to state ownership. In that year the government decided that motorway users have to pay only for the operation and maintenance costs, while the construction and financial costs should be covered from the state budget. The decision disposed of a unified vignette system which was introduced first on the M1 and M3 motorways in January 2000, cancelling the existing charging systems up to that time. Although the aggregated general toll rate was reduced by 50%, this step produced social dissatisfaction towards the vignette system, especially by the casual and mainly short section users. Despite, the traffic volumes on concerned motorways rose significantly with about 30% and the yearly revenues from toll collection dropped back by 35% (Siposs, 2002).

That time it was general, that weekly vignette users represented more than 50% of the total traffic, while monthly vignette users were about 10% and yearly vignette users were between 30% and 40% of the total traffic, depending on time and section (Siposs, 2002).

In 2003 a new section of M3 motorway, the new M30 motorway and the reconstructed M7 motorway joined the vignette system. In March 2004 the last element of the Hungarian motorway network, the M5 concession motorway also joined the vignette system (after negotiations and modification of the concession contract between the government and the concessionaire). This step allowed motorists to use more than 500 km motorways with a relatively cheap and simple tool (Tánczos et al., 2004b).

The vignette prices in 2004 (in HUF) were the following (see Table 2.):

	4-day					
Category	1 Dec 2003 – 30 April 2004	1 May 2004 – 30 Sept 2004	1 Oct 2004 – 31 Dec 2004	10-day	31-day	Yearly
PCs	970	1 270	970	2 000	3 400	30 500
LGVs	-	-	-	5 500	10 000	88 000
HGVs	-	-	-	8 500	14 500	130 000

Table 2: Vignette prices on the Hungarian motorways in 2004 (Source: State Motorway Management Company)

Recently there is a 650 km long motorway network in Hungary, which contains 536 km of motorway and 114 km of highway. The 7,0 km/1000 km2 value of network density is only approx. 40% of the similar factor in the EU 15.

In first half of 2004 vignette sales showed that PC users preferred 4-day vignettes in 70% of total sales, “weekly” (10-day) vignettes represented about 15%, monthly vignette users were about 10%, yearly vignette users were about 5%. LGV users bought “weekly” vignettes in 75%, monthly vignettes in 20% and yearly vignettes in 5%. Among HGV users “weekly” vignettes represented more than 70% of the total sales, while monthly vignette users were about 20% and yearly vignettes were about 10% of the total sales. From 1 January 2005 HGV category is split to two sub-categories, vehicles below and above 12 tons of total weight (according to relevant EU directives). Users with vehicles above 12 tons of total weight are allowed to buy also 1-day vignette created specially for this category.

Summarising, charging schemes so far were not based on exact calculations and on allocating the real infrastructure costs. As result of unification procedure, the introduced vignette system also cannot solve this problem. The dynamic extension of motorway network and the continuously growing traffic needs project the crucial need for cost proportional commitment of infrastructure users. The existing approach shall be changed to reach the desired goals and the set up of sustainable transportation system.

3. GAME THEORY APPLICATIONS IN ROAD TRANSPORT

In most of the countries the setting of road infrastructure charging schemes is very complicated. The several approaches in use are usually differing, therefore their calculations and impacts are not clearly comparable. Charging schemes could be worked out based on real costs of infrastructure provision or on revenue-generating potential of user categories. While the preceding approach aims to cover the real emerging costs, the latter one can consider number of economic, social and political point of views.

Researches of past years primarily focused on efficiency of existing applications and on cost characteristics of different user groups. Additionally, they analysed the desired cost allocation ratio among user groups in case of a new charging scheme to be introduced. Such reports were elaborated e.g. in the USA, in Austria, in Switzerland and recently in Germany. They aimed at covering real infrastructure costs using cost-, revenue- and traffic databases based on long-term time period.

However, in case of Hungary these preconditions are not at all or are only partially fulfilled. Traffic database is quite accurately documented from long time ago, but cost- and revenue accounts have been reported only in the past years. The reasons are widely known, the most relevant ones are the shortcomings of administrative system of planned economy and the politically emphasised need for infrastructure development that is motion power of growing economy, which played down the exact economic calculations (Tánczos et al., 2004a).

The EU integration process, the joining of Hungary to the European Union and the quite full adaptation of common regulations has forced out the revision and desired change of viewpoints mentioned above. Its consequences are the quasi detailed cost and revenue accounts in the past years, and the growing need for setting up a cost based charging system in the country.

Nevertheless, the process of satisfying all demands needs adaptation and application of new procedures taking into account the Hungarian circumstances. Such kind of procedures could be the game-theoretic concepts. But before analysing their applicability in Hungary, it is important to demonstrate and characterise them.

In case of game theory based cost allocation, first the players i of the allocation game shall be defined, generally they are the different user groups. This leads to a n-person game, where N = {1,2,…,i,…,n} is the set of the players. The single players are independent from each other and aim to achieve maximum individual gain (have minimum individual cost; c(i)) within the game. Searching for maximum profit potential is the denoted goal in every game. Players are ready to pass up their independency and in this wise form a coalition S, if they can reach higher level of gains (lower level of costs; c(S)), where S marks a subset of players N. Basic rule of coalition formation is that users join, if their benefits within the coalition are higher (costs are lower) than benefits (costs) when remaining independent. We assume that coalition formation has advantage over individuals. In such a case the overall goal is maximising the benefit of the coalition.

The achievable gain of player i is defined by the payoff function $\varphi(x) = \sum_i \varphi_i(x)$, where real vector x is the imputation, if $\sum_i x_i = v(N)$ and $x_i \geq v(i)$. The attitude of different coalitions is determined by the set of pure strategies of coalition S, i.e. X{S}. The characteristic function $v(N) = \max \min \varphi(x)$ of the game contains the maximum amount of gains of all possible coalitions, where x is the payoff (imputation) vector (Szidarovszky & Molnár, 1986).

Basic concept of cooperative games is defined as follows: in case of a given n-player game what coalitions can be formed by players and within these coalitions how the benefits should be split among the players? (Szidarovszky & Molnár, 1986)

In most cases, when allocating infrastructure cost based on game-theoretic concepts, practically the user groups shall be considered as coalitions.

3.1 The Core

The core of a game is that set of imputations, where $\sum_i x_i \geq v(S)$. While players of coalition S aim at increasing gains, every solution in the core is efficient and leads to stable solution of the game.

The disadvantage of this concept is that the core either could consist of many points or could also be empty. In these cases it could not provide acceptable cost allocation. Considering road infrastructure, economies of scale are so large that the core of such a game is always non empty (Lemaire, 1984). Furthermore, it plays an important role in judgement of other allocation schemes for their stability properties (Doll, 2004).

3.2 The Shapley-Value and Aumann-Shapley Prices

If we should choose one of the numerous solutions within the core, the Shapley-value helps as it is proved that the chosen cost allocation vector φ is efficient (the total value of the players is the value of the grand coalition), symmetric (allocated and emerged costs to all players are equal when joining the coalition), "dummy" (such a player does not contribute to coalition, his value shall be zero and player is called inessential) and additive (allocated costs could be calculated by the cost elements as well as by the characteristic function) (Shapley, 1953). Shapley appreciated the provision of benefit (cost) allocation by personal contribution to coalition. Term of Shapley-value defines the allocated costs of each player in coalition S.

We can arrive Shapley-value using the following simple expression:

$$x_i = \frac{1}{n!}\sum_{s}(s-1)!(n-s)![v(S) - v(S \setminus \{i\})],$$

where s denotes the number of players of coalition S.

In case of road infrastructure the problem could be expressed as follows: if new road section is opened, cost saving to be split among users shall be compared to a pro forma section opened only for that certain user category.

Property of approach is that due to differing bearing potential of user categories, the category saves more cost for coalition it wins more benefit, compared to individual cost saving. Practical application of Shapley-value is widely accepted but it needs very precise cost calculations. Therefore, this approach demands exact accounting of costs claimed by user categories.

The extended Shapley-value presents an opportunity to reduce computing Shapley-value in case of large number of players. We shall define maximum value of formation of N and suspect that every players of the game are equal sized and can be assigned to specific user categories. If we prove the assignment of each player in the game and this way we recognise the same evolved coalitions, we spare steps in the calculation. If we can save the structure of original problem when adapting to this approach and we only decrease its complexity, we can speed up calculation of Shapley-value.

Otherwise this method also cannot manage infinitely many players but the concept of Aumann-Shapley (1974) prices. There are several ways to reach the prices but all these approaches result in a single value, which means computing the average marginal costs of player i concerning all levels of total demand (Doll, 2004). The former (deriving) and latter mentioned (integrating) processes require continuous cost functions. Due to deriving this concept can not manage allocating fix cost elements to players. Mertens (1998) inverted the order of deriving and integrating, herewith he solved the problem of splitting fix cost elements.

3.3 The Nucleolus

Schmeidler (1969) introduced the concept named nucleolus. The nucleolus measures the attitude of coalition towards a proposed allocation by the difference between secured personal cost and proposed cost of coalition (Lemaire, 1984). This concept aims to minimise the maximum constraints, in other words to maximise the least outcomes of any players of coalition S.

The excess

$$e(x,s) = v(S) - \sum_{j \in S} x_j$$

measures the "happiness degree" of each coalition S (Lemaire, 1984). If this excess is negative, the proposed allocation does not belongs to the core, but if it is positive, then the allocation is equitable and acceptable assuming that the core exists.

Littlechild and Thomson (1977) elaborated its linear programming formula for estimating aircraft landing fees at Birmingham airport. Their applied fairness criteria and programming steps can be adapted also to user category defined cost allocation problems. We should use the following simplification: we should apply fair cost allocations where difference in allocated costs on commonly used road section between a user with higher capacity demand and other users are not higher than on road sections assigned separately to user groups. The linear program shall be built up by sorting user categories by total weight of vehicles and the fairness criteria shall be fulfilled. Due to comparable cost values mentioned above this concept requires also a very detailed and complex database.

3.4 Oligopoly games

The oligopoly game concept belongs – contrary to previously presented approaches – to non-cooperative games. If we apply this concept we assume that players are not regarding interests of other players. In this case we look user categories as players themselves. This concept is not widely applied to road infrastructure cost allocation problems, but this study analyses its adaptability and applicability.

Oligopoly games are one of the best-known game-theoretic problems, they present specific, often appearing economic situations. In case of road infrastructure we can define the following problem: the road authority wants to inspire the keeping (or improving) the existing level of service on road at increasing traffic volumes. Therefore, it initiates construction of a new motorway section. The potential users may use this new section, if they pay specific user charges. In this situation the question to be answered is how much the user charges shall be for being worth using it for everybody. The oligopoly game concept answers this question. Let x_k be the traffic volume of user category k, $\varphi(\sum_i x_i)$ be the specific user charge and be H_k the benefit of user category k when using the motorway section.

We shall maximise the difference between benefits and costs for all user categories:

$$H_k(x_k) - x_k \varphi(\sum_i x_i) \rightarrow \max!$$

This approach is simple and requires no detailed and complex cost database.

4. ADAPTABILITY AND COMPARISON TO THE HUNGARIAN CASE

In order to analyse adaptability of concepts described above, first we shall examine which is effectively applicable in road infrastructure cost allocation game.

The practice in the USA highlighted the effective solubility of road infrastructure cost allocation, but solution of this problem requires adequate long-term and complex cost databases. There were attempts to apply these methods also in Europe, but successful application also needed appropriate data provision. Villarreal-Cavazos (1985) and Makrigeorgis (1991) regarded user categories as players. In contrary Castano-Pardo & Garcia-Diaz (1995) considered every single vehicle movements as players and with this created a nonatomic-game with infinitely many players. Their model is applied to a pro forma motorway section by allocating construction and maintenance costs to four different user categories.

Computing Mertens sort of Aumann-Shapley prices presumes cognising exact cost functions. Doll (2004) solved this problem by dealing with differential quotients rather than derivatives. This step introduced a “smoothing factor”. Choosing value of factor can influence the number of steps and time-need of computation considerably.

Application of oligopoly game – due to its simple structure and similar properties to other concepts mentioned above – also does not meet obstacles.

When analysing applicability of different methods in the Hungarian circumstances, we have to return to history. As we highlighted in introduction, specialities of Hungarian circumstances resulted different charging policy setting compared to Western European countries. Although most of the policies became EU-compatible, constraints of past years and decades set back applications of state-of-the-art solutions still up to now. The present state of knowledge of this study is that the domestic input data are not accurate for running complex models. Therefore we chose the oligopoly game concept as first move in this research.

We collected data from published professional estimations or official sources (Tánczos & Bokor, 2004; Timár, 2004). The generated model is very simple and far not complete, it needs further extension and specifying, this will be the next step of research in the future.

First we shall define the characteristic function as starting-point. Because its complexity affects time-need of computation considerably, practically we chose a simplified characteristic function.

Let us suppose that specific construction cost of motorway in Hungary is 2000 million HUF / km (in 2004). During the generally accepted 35 years of lifetime in Hungary, considering depreciation and periodic reconstruction costs, summing up we assume 66 million HUF / km of “construction” costs. According to own estimations, the Hungarian Motorway Management Co. Ltd. spent approx. 6000 million HUF on operation and 9000 million HUF on maintaining the 500 km long motorway network. In the course of calculations we took into account 12000 vehicles as AADT, and a 80% - 20% PC - HGV traffic distribution ratio. During the use of motorway section the users can save direct and indirect costs, for PCs supposing 15 HUF / veh / km, for HGVs supposing 30 HUF / veh / km.

The aim of computation is maximising user benefits by choosing optimal value of user charges. For this we regarded the following constraints: user charges shall not exceed user benefits, revenues from user charges shall exceed occasioned costs of user categories. Maintenance cost is assumed depending on traffic distribution and volume, other costs are regarded with average values.

The result of generated model showed that charges are too high if we consider construction, operation and maintenance costs. This result proves the current Hungarian ministerial decree in force which declares that revenues from motorway user charges shall cover only operation and maintenance costs.

Thus, we passed over construction costs when running the model second time. This time we achieved results that we could evaluate. In case of PCs the user charge is set for 4,8 HUF / veh / km, for HGVs 15,09 HUF / veh / km. We compared the model results to real user charges from 2004. In case of vignettes it is hard to demonstrate an average specific toll rate, therefore we supposed an average frequent use of the motorway network. It is supposed, that a 4-day vignette (only for PCs) is used twice, a 10-day one 4 times, a 30-day one 10 times and a yearly vignette 104 times. Additionally, we assumed a 240 km long user travel. This way of assumption gives a 3,5 HUF / veh / km rate, which is lower to some degree than 4,8 HUF / veh / km value of the model. In the same way the 11,65 HUF / veh / km value from vignette prices also lower than computed 15,09 HUF / veh / km value. Model result shows, that motorway company earns 15000 million HUF revenue from user charges, and can meet the expenses.

However, the current decree about rate of user charges shall be considered as temporary regulation. Professional and political views concur on necessity of set up a self financing motorway system in Hungary. Nevertheless, it demands inclusion of infrastructure construction costs into charges. With help of calculation method detailed above we can estimate these user charges. For this we shall increase the value of user benefits, e.g. to 50-50 HUF / veh / km value. After running the model third time, the charges ran high for PCs to 19,89 HUF / veh / km (more than 4x rise in prices), for HGVs to 30,17 HUF / veh / km (approx. 2x appreciation). Compared to rates on German motorway network, the model results are quite the same as the German charges (30,20 HUF / veh / km using 251,68 HUF / EUR yearly average conversion rate of National Bank of Hungary from 2004). However, user charges in Austria are far higher – due to the well known reasons.

5. CONCLUSIONS

In the scientific literature there are numerous studies about cost allocation solutions based on game-theoretic methods, but despite of their applicability these methods could not be applied widely in practice. Moreover, several specific, unique solutions are in use, which can be adapted more precisely to given circumstances. Nevertheless, in such an environment as e.g. in Hungary, where current calculations are not standing on certain scientific base, these methods can be effectively applied to validate calculations or they can prepare the implementation of a new methodological base for fair and equal cost allocation. The first results of this research point out, that charging systems based on practical experiences can be effectively applied in given circumstances, but they are in crucial need of scientific bases to also prove their efficiency. It is essential to improve the calculation method described above. We can definitely state that the improvement and reform of charging systems in accord with efforts of the European Union demand the application of mathematical methods.

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