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Comparative Analysis of the Economic Sustainability of Transport Systems Served by Alternative and Conventional Buses and Coaches

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ABSTRACT

Today's economic and social environment faces several problems and challenges (e.g. energy crisis, inflation, environmental protection), most of which interact with the transport system in two directions. Researchers and relevant organisations have developed several proposals and action plans to mitigate the 'problem cloud' for each mobility subsystem, but these tend to focus on a technological, economic or industrial solution rather than a complex one. This includes subsidising the purchase and operation of electric vehicles, encouraging the use of public transport, and developing soft modes of transport. This study develops a multi-layered, complex, cost-oriented methodology to increase the sustainability and economic stability of local and interurban bus and coach public transport. The methodology based on the main technical and operational (maintenance, energy use and storage) parameters of different conventional and alternative propulsion vehicles, as well as on the available forms of financing, taking into account discount rates. The procedure developed will be illustrated with examples from Hungarian cities. The unit costs per kilometre of the different propulsion systems will be examined. The method can be used to determine the most economically efficient and sustainable choice of vehicle propulsion for the public transport service provider, and to obtain a realistic picture of unit costs.

KEYWORDS

alternative propulsion buses; electric bus; diesel bus; kilometre based unit cost; economically efficient local public transport.

1. INTRODUCTION

The modernisation of the propulsion of buses is a new area of research. It is only a few years old. Following an international overview, this paper proposes an economic comparison of propulsion systems in a coherent, integrated and transparent framework.

Table 1 – Some of the literature examined

Nr	Title	Author, Journal
[1]	Review of the estimation methods of energy consumption for battery electric buses	Al-Ogaili, 2021 – Energies
[2]	Life cycle CO_2 footprint reduction comparison of hybrid and electric buses for bus transit networks	García, 2022
[3]	Decarbonising ships, planes and trucks: An analysis of suitable low-carbon fuels for the maritime, aviation and haulage sectors	Gray, 2021 – Advances in applied energy

Nr	Title	Author, Journal
[4]	Hybrid electric vehicles and their challenges: A review	Hannan, 2014 – Renewable & Sustainable Energy Reviews
[5]	A probabilistic fleet analysis for energy consumption, life cycle cost and greenhouse gas emissions modelling of bus technologies	Harris, 2020 – Applied Energy
[6]	Energy consumption and cost-benefit analysis of hybrid and electric city buses	Lajunen, 2014 – Transportation Research Part C-emerging
[7]	The role of alternative fuel buses in the transition period of public transport electrification in Europe: a lifecycle perspective	Lu, 2022 – International Journal of Sustainable Transportation
[8]	Evaluating automobile fuel/propulsion system technologies	MacLean, 2003 – Progress in Energy and Combustion Science
[9]	Electric buses: A review of alternative powertrains	Mahmoud, 2016 – Renewable & Sustainable Energy Reviews
[10]	What hinders adoption of the electric bus in Canadian transit? Perspectives of transit providers	Mohamed, 2017 – Transportation Research Part D-transport and Environment
[11]	A spatially explicit optimisation model for the selection of sustainable transport technologies at regional bus companies	Pinamonti, 2021 – Optimisation and Engineering
[12]	Contribution of country-specific electricity mix and charging time to environmental impact of battery electric vehicles: A case study of electric buses in Germany	Rupp, 2019 – Applied Energy
[13]	Analysis of Global and Local Environmental Impacts of Bus Transport by LCA Methodologies	Simon, 2010
[14]	Life cycle cost assessment of urban buses equipped with conventional and alternative propulsion drive	Szumska, 2018
[15]	Life cycle cost (LCC) level of an urban transport fleet with Differentiated share of buses with alternative drive systems	Szumska, 2020
[16]	Can propulsion and fuel diversity for the bus fleet achieve the win-win strategy of energy conservation and environmental protection?	Wang, 2015 – Applied Energy
[17]	Operational lifecycle carbon value of bus electrification in Macau	Xu, 2020 – Sustainability
[18]	A review on the state-of-the-art technologies of electric vehicle, its impacts and prospects	Yong, 2015 – Renewable & Sustainable Energy Reviews
[19]	Impact of the electric mobility implementation on the greenhouse gases production in central European countries	Skrúcaný T, Kendra M, Stopka O, Milojević S, Figlus T, Csiszár C., 2019 – Sustainability
[20]	Environmental sustainability of the vehicle fleet change in public city transport of selected city in Central Europe	Konečný V, Gnap J, Settey T, Petro F, Skrúcaný T, Figlus T., 2020 - Energies
[21]	Environmental comparison of different transport modes	Skrúcaný, T., Kendra, M., Kalina, T., Jurkovič, M., Vojtek, M. i Synák, F., 2018 – Naše More

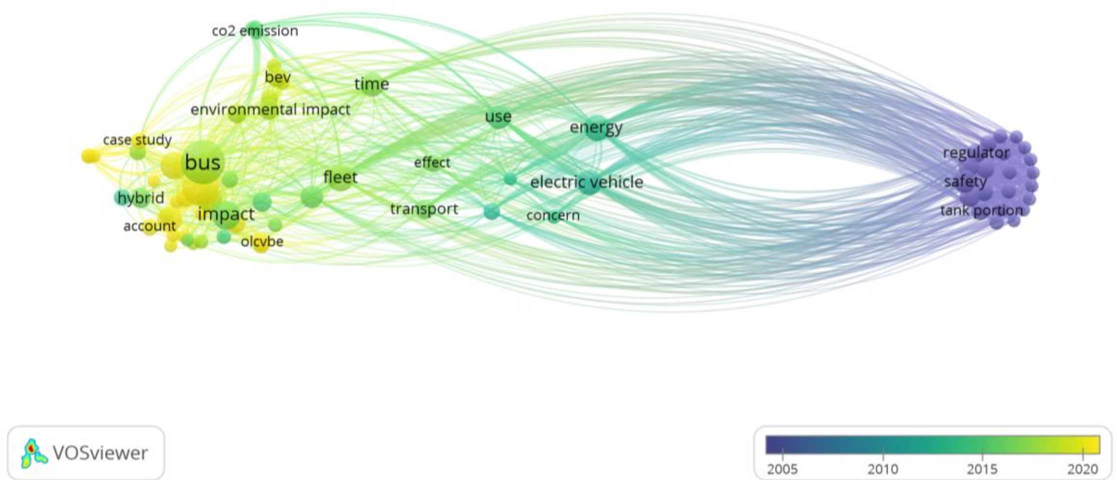

Figure 1 – Articles on alternative bus propulsion (own editing)

The analysis of literature overview shows that the investigated topic has dynamically evolved. The first older (blue) cluster shows that priority of analysis was safety of new technologies. After that (green) the scope of analysis shifted to energy efficiency and environmental impact assessment on local level. The third cluster (yellow) is the newest one with life cycle cost analysis and risk assessment of alternative drive chains in public transport. It is important to point out that a number of studies have been carried out to determine the propulsion of buses, but these have analysed the choice of the ideal vehicle from an environmental rather than an economic point of view. Consequently, the authors see the need to develop a methodology, mainly from an economic point of view, which can be used as a kind of decision-preparatory method in the planning of the transport system, service.

In Hungary, local and interurban public transport is provided based on public service contracts between the organisations responsible for providing services and bus operators. According to Act XLI of 2012 on Passenger Transport Services, the Minister responsible for transport (currently the Minister of Construction and Transport) is responsible for the maintenance of interurban bus services, while the competent municipalities are responsible for the provision of local public transport services, except for the capital, as a voluntary task. In all cases, customers must compensate the operators for any losses incurred due to the service, the method and extent of which are laid down in the public service contracts.

The public service may be awarded for a maximum period of ten years following Article 4(3) of Regulation (EC) No 1370/2007 (exact title: Regulation (EC) No 1370/2007 of the European Parliament and of the Council of 23 October 2007 on public passenger transport services by rail and by road and repealing Council Regulations (EEC) Nos 1191/69 and 1107/70). Therefore, it is in the commercial interest of the operator to set the total life cycle cost (LCC) of the buses at ten years.

The Hungarian practice in the field of local public transport differs significantly from this: in many cases, municipalities make use of the possibility of a so-called forced withdrawal for 1–2 years – as allowed by law – due to the invalidity of the tender for the public service, and there are also dilemmas between the contracting parties regarding the amount of compensation mentioned above, given the real operating costs. This is compounded by the fact that, in the increasingly widespread use of innovative, environmentally friendly propulsion systems, the service provider can only estimate the operating costs due to a lack of operating experience, which entails a significant business risk for both parties (the service provider may pass this on to the customer).

This methodology addresses the above problem by providing an approximate unit cost for the different types of buses (diesel, electric, CNG, CBG, diesel-electric, hydrogen) for the whole public service period. In addition, by comparing the cost values of each propulsion system, it is possible to select a sustainable and efficient propulsion system for the local public transport system, both from a transport and a social point of view.

2. METHODOLOGY

The notations used in the methodology are given in *Table 2*.

Table 2 – Notations used in the methodology

Variable marking	Changing technical content	Dimension
j	Vehicle propulsion mode	[-]
t	The service life of the vehicle's primary fuel tanks	[year] or [charge life cycle]
q	The service life of the vehicle's secondary fuel tanks	[year] or [charge life cycle]
x	Number of primary fuel tanks in the vehicle	[db]
y	Number of secondary fuel tanks in the vehicle	[db]
k	The capacity of the vehicle's primary fuel tanks	[litres] or [kWh]
l	The capacity of the vehicle's secondary fuel tanks	[litres] or [kWh]
$C_{price,j}$	Total purchase cost of vehicles with *j* drive modes in case of lump sum payment	[€]
$N_{j_{t,q,x,y,k,l}}$	Number of vehicles with *t,q* service life, *x,y* number of units, *k,l* capacity of energy storage, *j* propulsion	[db]

Variable marking	Changing technical content	Dimension
${c_j}_{t,q,x,y,k,l}$	Cost of purchasing a vehicle with *t,q* lifetime, *x,y* number of units, *k,l* capacity of energy storage, *j* propulsion in case of a lump sum payment	[€/vehicle]
$C_{loan,j}$	Aggregate purchase cost of *j*-drive vehicles for a loan contract	[€]
${P_j}_{t,q,x,y,k,l}$	The part of the purchase cost per year of a vehicle with *t,q* lifetime, *x,y* number of units, *k,l* capacity, *j* propulsion, for a credit agreement	[€/vehicle/year]
$\bar{L}_{j_{t,q,x,y,k,l,n}}$	Annual average mileage of a vehicle with *t,q* lifetime, *x,y* number of units, *k,l* capacity of energy storage, *j* propulsion, in year *n*	[km/year]
$F_{j_{t,q,x,y,k,l}}$	Specific consumption per 100 km of a vehicle with *t,q* lifetime, *x,y* number of units, *k,l* capacity of energy storage, *j* propulsion	[l/100 km] or [kg/100 km] or [kWh/100 km]
S_j	Specific fuel cost for *j* drive mode	[€/l] or [€/kg] or [€/kWh]
$\varphi_{j,n}$	Projected change in fuel costs for fuel mode *j*, year *n*	[%]
n	Length of the study period (public service contract) (*n=1...m*)	[year]
D^n	Discount rate for the year	[%]
$C_{energy,j}$	Cost of energy use and storage aggregated by *j* drive mode	[€/duration]
$R_{electric}$	The replacement cost of storing 1 kWh of electricity (1 kWh ≈ \$152 ≈ €142.26) [22], [23]	[€/1 kWh]
R_{j_k}	Cost of replacing energy storage with capacity *k* per gas (*j=IV or j=V)* drive mode	[€/energy storage]
$T_{j,n}$	Number of refuelling operations in year *n* for electric (*j=II or j=III or j=V)* traction	[units/year]
$C_{energy,loan,j}$	Cost of energy use and storage, aggregated by type of operation in *the* case of a credit agreement for storage	[€/duration]
$M_{electric}$	Replacement cost of storing 1 kWh of electricity for a credit agreement over one year	[€/1 kWh/year]
M_{j_k}	Cost of replacement of energy storage with capacity *k per* gas (*j=IV or j=V)* drive mode for a credit agreement per 1 year	[€/energy storage/year]
α	The bus operator carries out all maintenance interventions throughout the life of the bus	[-]
g	Warranty maintenance	[-]
s	Maintenance under a partnership contract	[-]
$c_{k,j,\alpha}$	Specific annual maintenance cost (*α*) by bus operator *j* per mode of propulsion	[€/vehicle/year]
$c_{k,g,j}$	Specific, annual, under-warranty (*g*) maintenance cost *j* per drive type	[€/vehicle/year]
$c_{k,j,sz}$	Specific annual maintenance cost(*s*) per drive type, carried out within the framework of a partnership contract	[€/vehicle/year]
$C_{k\ total,j}$	Cumulative maintenance costs for vehicles with *j* drive modes over a given period	[€/duration]
$c_{j,ga}$	Cost of vehicle tax per year for vehicles with *j* drive modes	[€/vehicle/year]
$c_{j,biz}$	The combined annual cost of compulsory liability insurance and CASCO insurance for vehicles with *j* drive modes	[€/vehicle/year]
$c_{j,refuel}$	Annual cost of lubricants and tyres for *j*-drive vehicles	[€/vehicle/year]
z	The form of financing for the charging infrastructure (lump sum: *z=0*, or lease contract *z=1*)	[-]
$C_{j,refuel,z}$	Cost of laying charging infrastructure for *j* drive mode	[€] or [€/year]
$C_{e\ total,j}$	Other costs calculated for the duration of the study *j* for the mode of operation	[€/lifetime]
B_{aid},j	The amount of aid received *j* for each type of drive	[€/vehicle/year]
$C_{total,j}$	Total lifetime and fleet cost reduced by subsidies *j* per the mode of propulsion	[€/fleet/duration]
$c_{unit,j}$	Specific running cost per km for *j* drive mode	[€/km]

The costs associated with maintaining bus and coach transport are examined in a complex way in this methodology, the structure of which and the interrelationships between the elements are shown in *Figure 2*.

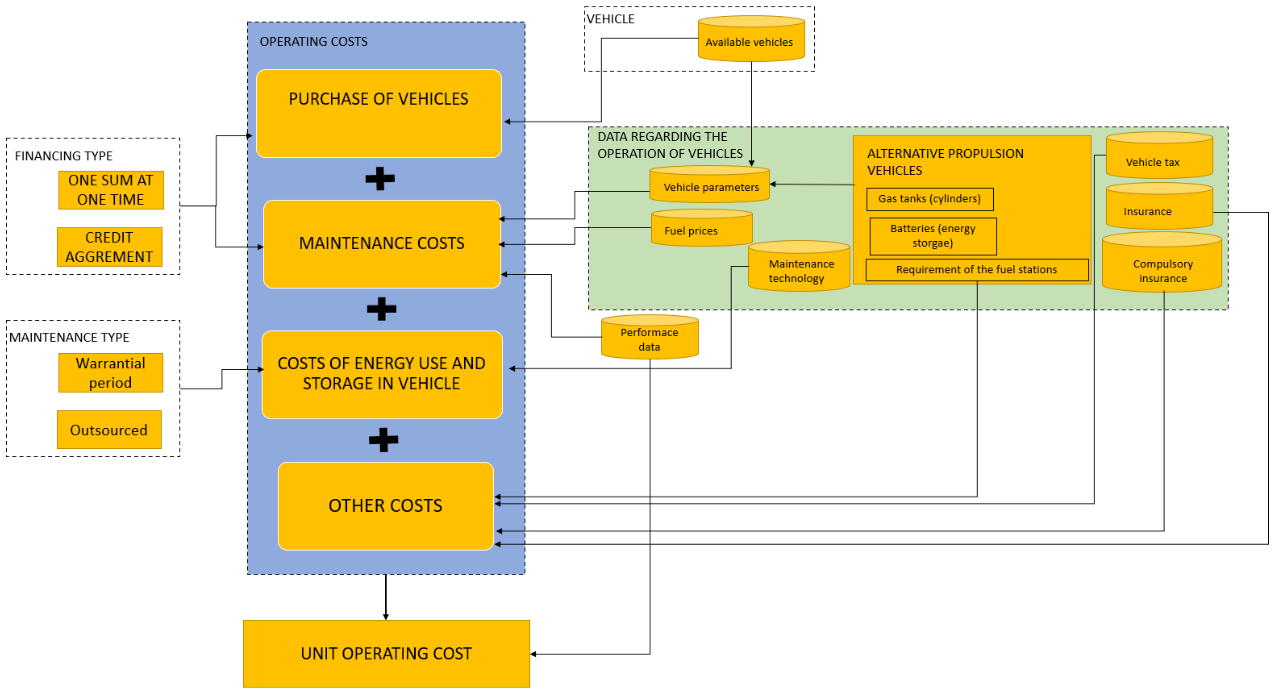

Figure 2 – Methodology structure (own edition)

The methodology developed considers not only the operating costs but also the different financing schemes, the duration of the study (i.e. the duration of the public service contract between the customer and the operator) and the discount rate describing the future change in money. The latter is particularly important in accurately determining the costs incurred by the service provider throughout the contract. A discount rate was used, considering the average inflation value of the last years (including the effects of the global economic crisis, the fluctuations in COVID-19) and the MNB's (Hungarian National Bank) forecast. The time interval can be determined based on the length of the public service contract (maximum 10 years regarding the mentioned European Regulation) and recalculated based on the inflation and the forecast.

The methodology applies to all bus and coach propulsion modes, including the powertrain, which may have the parameters of *Table 3* for the test.

Table 3 – Characteristics of different propulsion systems

Drive mode	Serial number (j)	Fuel storage method		Fuel storage lifetime		Number of fuel tanks		Fuel storage capacity	
		Primary	Secondary	Primary (t)	Secondary (q)	Primary (x)	Secondary (y)	Primary (k)	Secondary (l)
Diesel	*I*	liquid fuel tank	-	lifetime of the vehicle	-	1	-	50–400 litres	-
Diesel-electric (hybrid)	*II*	liquid fuel tank	battery packs	lifetime of the vehicle	4–10 years	-	-	50–400 litres	20–100 kWh
(Full) Electric	*III*	battery packs	-	2.000–4.000 charge life cycle	-	-	-	200–500 kWh	-
CNG (CBG)	*IV*	gas tanks	-	8–20 years	-	2–12 pieces	-	30–150 litres	-
Hydrogen	*V*	gas tanks	battery packs	8–20 years	4–10 years	2–5 pieces	-	30–50 litre	20–100 kWh
LPG	*VI*	LPG tank	-	10 years	-	1–3 piece	-	30–150 litres	-

Based on the table, different compositions of buses can be defined per powertrain within each powertrain, determined by the lifetime and number of fuel tanks and their capacity ($j_{t,q,x,y,k,l}$) as follows (these categories and the parameters assigned to them are also the cost category formers):

- Diesel (I): the life of the tank is the same as that of the vehicle, and its numerical value (in the vast majority of cases) is 1, so the capacity of the tank determines the type (I_k capacity of the tank varies between 50 and 400 litres depending on the vehicle design (mini, midi, solo, articulated).
- Diesel-electric (hybrid) (II): the parameters of the primary energy source (diesel unit) are the same as described above. The electric part – as a secondary energy source – is determined by the lifetime and capacity of the battery packs and can be interpreted as the sum of the two ($I_k + II_{q,l}$). Hybrid vehicles typically have a smaller electrical energy storage capacity (20–100 kWh) with a lifetime of 4–10 years (as committed by the manufacturer).
- (Full) Electric (III): the drive for the test is determined by the lifetime of the energy storage (2,000–4,000 charge life cycles) and its capacity (200–500 kWh) ($III_{t,k}$). The replacement cost of an electric storage unit is proportional to the amount of energy stored rather than the number of units.
- For buses and coaches (IV) fuelled by compressed natural gas (CNG) or compressed biogas (CBG), the vehicle's powertrain is determined by the life expectancy (8–20 years, depending on disaster management rules), the number of gas tanks (2–12) and their capacity (30–150 litres) ($IV_{t,x,k}$). The number of on-board tanks may vary from one vehicle manufacturer (and in many cases from one type) to another, and their capacity, although catalogued, can be tailored to individual needs. Since the construction of CNG and CBG vehicles does not differ, only the technology used to produce the propellant, the methodology treats CBG vehicles as CNG-powered.
- Hydrogen (V): the vehicle's primary energy source is hydrogen gas, which is stored in high-pressure tanks (350 bar) on the vehicle's roof. The number (2–5) and capacity (30–50 litres) of these tanks and their lifetime is 8–20 years, depending on safety regulations. As a secondary energy source, the electric unit typically helps with acceleration and overcoming rough terrain. The lifetime and capacity of the electric storage is similar to the diesel-electric drive (4–10 years; 20–100 kWh). Hydrogen propulsion can thus be defined as the sum of a gas-powered and an electric-powered sub-unit ($V_{q,y,l} + II_{t,k}$)
- LPG (VI): each composition is determined by the number of LPG containers (1–3) and their capacity (30–150 litres) ($VI_{x,k}$).

The methodology distinguishes four different costs for the provision of bus transport:

- Costs for the purchase of vehicles;
- Costs of energy use and storage in vehicles;
- Maintenance costs for buses;
- Other costs.

Limitations of the methodology include the fact that it does not consider the human resource costs (e.g. drivers, maintenance staff, traffic attendants, engineers) needed to provide the service. This is due to the diversified material compensation of jobs. In order to estimate the human resources cost, it is necessary to know exactly the number of workers assigned to each task, which is largely determined by the maintenance, IT and communication systems used. As these factors are service provider or public service-specific, they are not considered in the present methodology due to possible distortions in the calculated cost values.

The variables used in the methodology provide a wide range of cost options, but the future values of some parameters (e.g. fuel price changes and/or discount rate) can only be estimated annually. Consequently, the values of time-related variables can be provided (with a single value) over the whole service period.

The calculation of the purchase costs is the same for buses with different propulsion systems (*j*): it is the sum of the number of vehicles to be purchased multiplied by the unit value of each bus with each propulsion system combination if the vehicles are purchased in one sum and at one time. Note that the methodology takes into account one vehicle price per powertrain (irrespective of manufacturer), assuming that the best offer is accepted by the tenderer for the procurement.

$$C_{price,I} = \sum_{k=50}^{400} N_{I_k} * c_{I_k} \quad (1)$$

$$C_{price,II} = \sum_{k=50}^{400} \sum_{q=2000}^{4000} \sum_{l=20}^{100} N_{I_k+II_{q,l}} * c_{I_k+II_{q,l}} \quad (2)$$

$$C_{price,III} = \sum_{t=2000}^{4000} \sum_{k=200}^{500} N_{III_{t,k}} * c_{III_{t,k}} \tag{3}$$

$$C_{price,IV} = \sum_{t=8}^{20} \sum_{x=2}^{12} \sum_{k=30}^{150} N_{IV_{t,x,k}} * c_{IV_{t,x,k}} \tag{4}$$

$$C_{price,V} = \sum_{t=8}^{20} \sum_{x=2}^{5} \sum_{k=30}^{50} \sum_{q=2000}^{4000} \sum_{l=20}^{100} N_{V_{t,x,k}+II_{q,l}} * c_{V_{t,x,k}+II_{q,l}} \tag{5}$$

$$C_{price,VI} = \sum_{x=1}^{3} \sum_{k=30}^{150} N_{VI_{x,k}} * c_{VI_{x,k}} \tag{6}$$

The methodology also treats purchases under credit agreements for a specified period, which do not include any other cost of assumption (e.g. maintenance, repair) by the creditor. In this case, the costs are not only exclusively incurred in the first year but are spread over the entire loan repayment duration and charged at a discount rate (7, 8, 9, 10, 11, 12).

$$C_{loan,I} = \sum_{n=1}^{m} \sum_{k=50}^{400} N_{I_k} * P_{I_k} * D^n \tag{7}$$

$$C_{loan,II} = \sum_{n=1}^{m} \sum_{k=50}^{400} \sum_{q=4}^{10} \sum_{l=20}^{100} N_{I_k+II_{q,l}} * P_{I_k+II_{q,l}} * D^n \tag{8}$$

$$C_{loan,III} = \sum_{n=1}^{m} \sum_{t=2000}^{4000} \sum_{k=200}^{500} N_{III_{t,k}} * P_{III_{t,k}} * D^n \tag{9}$$

$$C_{loan,IV} = \sum_{n=1}^{m} \sum_{t=8}^{20} \sum_{x=2}^{12} \sum_{k=30}^{150} N_{IV_{t,x,k}} * P_{IV_{t,x,k}} * D^n \tag{10}$$

$$C_{loan,V} = \sum_{n=1}^{m} \sum_{t=8}^{20} \sum_{x=2}^{5} \sum_{k=30}^{50} \sum_{q=4}^{10} \sum_{l=20}^{100} N_{V_{t,x,k}+II_{q,l}} * P_{V_{t,x,k}+II_{q,l}} * D^n \tag{11}$$

$$C_{loan,VI} = \sum_{n=1}^{m} \sum_{x=1}^{3} \sum_{k=30}^{150} N_{VI_{x,k}} * P_{VI_{x,k}} * D^n \tag{12}$$

The methodology takes into account different parameters for the costs of energy use and storage, adapted to the specific technical characteristics of each powertrain and within it of the powertrain assemblies:

- *I*: There is no cost for an energy storage tank, as the lifetime of the tank is the same as the lifetime of the vehicle;
- *II*: Diesel units are as described above, but replacing electric energy storage may be necessary based on the ratio between the number of charges per year and the lifetime of the batteries. The cost of replacing battery packs is based on the world market price for storing 1 kWh of energy;
- The calculation of energy storage costs for drive *III* is the same as for the electrical part of drive *II*;
- For *IV* buses and coaches, high-pressure (200–220 bar) gas cylinders may need to be replaced, determined by the certification period of the cylinders (maximum lifetime as specified in the regulations). The cost of this depends on the service life, capacity and number of tanks;
- Replacing the energy storage of a *V* bus or coach combines the energy storage described for drives *II* and *IV*. The lifetime, capacity and number of high-pressure (350 bar) tanks storing the primary energy source determine the cost of the tanks, while the cost per 1 kWh of replacing the secondary battery packs is based on the number of charges per year and the lifetime of the energy storage tanks;

— *VI*: the cost of replacing energy storage tanks depends on their number and capacity. Since the lifetime of the storage tanks is equal to or longer than the duration of the contract for the bus transport service, the replacement cost has not been considered in the methodology.

Energy use and storage costs are also considered, which are the costs resulting from the amount of energy used to move the vehicle and its price on the world market. The former is derived from the average annual mileage and average (specific) energy consumption per kilometre for each powertrain composition, while the latter is derived from the current fuel price and its forecasted change. As the world fuel price is sensitive to geopolitical influences, the trend of the counter values over the last five years provides a basis for estimating the changes, the data source being documents published by various international organisations [24, 25, 26, 27].

The energy use and storage costs per drive, calculated above, are shown in *Equations (13, 14, 15, 16, 17, 18).*

$$C_{energy,I} = \sum_{n=1}^{m}\sum_{k=50}^{400} N_{I_k} * D^n * \frac{F_{I_k}}{100} * \bar{L}_{I_k,n} * S_I * \varphi_{I,n} \tag{13}$$

$$\begin{aligned} C_{energy,II} = {} & \sum_{n=1}^{m}\sum_{q=4}^{10}\sum_{l=20}^{100} N_{II_{q,l}} * D^n * (l * R_{electric} * \frac{T_{II,n}}{q} + \frac{F_{II_{q,l}}}{100} * \bar{L}_{II_{q,l},n} * S_{II} * \varphi_{II,n}) \\ & + \sum_{n=1}^{m}\sum_{k=50}^{400} N_{I_k} * D^n * \frac{F_{I_k}}{100} * \bar{L}_{I_{k,n}} * S_I * \varphi_{I,n} \end{aligned} \tag{14}$$

$$C_{energy,III} = \sum_{n=1}^{m}\sum_{t=2000}^{4000}\sum_{k=200}^{500} N_{III_{t,k}} * D^n * (k * R_{electric} * \frac{T_{III,n}}{t} + \frac{F_{III_{t,k}}}{100} * \bar{L}_{III_{t,k,n}} * S_{III} * \varphi_{III,n}) \tag{15}$$

$$C_{energy,IV} = \sum_{n=1}^{m}\sum_{t=8}^{20}\sum_{x=2}^{12}\sum_{k=30}^{150} N_{IV_{t,x,k}} * D^n * (R_{IV_k} * x * \frac{n}{t} + \frac{F_{III_{t,x,k}}}{100} * \bar{L}_{III_{t,x,k,n}} * S_{IV} * \varphi_{IV,n}) \tag{16}$$

$$\begin{aligned} C_{energy,V} = {} & \sum_{n=1}^{m}\sum_{t=8}^{20}\sum_{x=2}^{5}\sum_{k=30}^{50}\sum_{q=4}^{10}\sum_{l=20}^{100} N_{V_{t,x,k}+II_{q,l}} * D^n * (l * R_{electric} * \frac{T_{III,n}}{q} + \frac{F_{II_{q,l}}}{100} * \bar{L}_{II_{q,l},n} * S_{II} * \varphi_{II,n} + R_{V_k} \\ & * x * \frac{n}{t} + \frac{F_{V_{t,x,k}}}{100} * \bar{L}_{V_{t,x,k}} * S_V * \varphi_{V,n}) \end{aligned} \tag{17}$$

$$C_{enery,VI} = \sum_{n=1}^{m}\sum_{x=1}^{3}\sum_{k=30}^{150} N_{VI_{x,k}} * D^n * (R_{VI_k} * x * \frac{n}{t} + \frac{F_{VI_{x,k}}}{100} * \bar{L}_{VI_{x,k}} * S_{VI} * \varphi_{VI,n}) \tag{18}$$

Taking into account the world market price of the above energy storage devices, the methodology also allows for the possibility of purchasing them under a credit agreement (19, 20, 21, 22, 23) (note that the latter option is not yet widely used but may become a realistic option in the future as technologies evolve). It is understood that in the case of drive mode *I*, in the absence of a replacement energy storage device, (13) is the relevant one.

$$\begin{aligned} C_{energy,loan,II} = {} & \sum_{n=1}^{m}\sum_{q=4}^{10}\sum_{l=20}^{100} N_{II_{q,l}} * D^n * (l * M_{electric} * \frac{T_{II,n}}{q} + \frac{F_{II_{q,l}}}{100} * \bar{L}_{II_{q,l,n}} * S_{II} * \varphi_{II,n}) + \sum_{k=50}^{400} N_{I_k} * D^n \\ & * \frac{F_{I_k}}{100} * \bar{L}_{I_{k,n}} * S_I * \varphi_{I,n} \end{aligned} \tag{19}$$

$$C_{energy,loan,III} = \sum_{n=1}^{m}\sum_{t=2000}^{4000}\sum_{k=200}^{500} N_{III_{t,k}} * D^n * (k * M_{electric} * \frac{T_{III,n}}{t} + \frac{F_{III_{t,k}}}{100} * \bar{L}_{III_{t,k},n} * S_{III} * \varphi_{III,n}) \tag{20}$$

$$C_{energy,loan,IV} = \sum_{n=1}^{m}\sum_{t=8}^{20}\sum_{x=2}^{12}\sum_{k=30}^{150} N_{IV_{t,x,k}} * D^n * (M_{IV_k} * x * \frac{n}{t} + \frac{F_{III_{t,x,k}}}{100} * \bar{L}_{III_{t,x,k},n} * S_{IV} * \varphi_{IV,n}) \tag{21}$$

$$C_{energy,loan,V} = \sum_{n=1}^{m}\sum_{t=8}^{20}\sum_{x=2}^{5}\sum_{k=30}^{50}\sum_{q=4}^{10}\sum_{l=20}^{100} N_{V_{t,x,k}+II_{q,l}} * D^n * (l * M_{electric} * \frac{T_{II,n}}{q} + \frac{F_{II_{q,l}}}{100} * \bar{L}_{II_{q,l,n}} * S_{II} * \varphi_{II,n} + M_{V_k} * x * \frac{n}{t} + \frac{F_{V_{t,x,k}}}{100} * \bar{L}_{V_{t,x,k,n}} * S_V * \varphi_{V,n}) \quad (22)$$

$$C_{enery,loan,VI} = \sum_{n=1}^{m}\sum_{x=1}^{3}\sum_{k=30}^{150} N_{VI_{x,k}} * D^n * (M_{VI_k} * x * \frac{n}{t} + \frac{F_{VI_{x,k}}}{100} * \bar{L}_{VI_{x,k},n} * S_{VI} * \varphi_{VI,n}) \quad (23)$$

Maintenance costs are incurred throughout the life of the vehicle. In addition to mayor repairs (e.g. repair or replacement of parts damaged in an accident or failing before their scheduled time), planned preventive maintenance processes, as used by transport companies and recommended by many bus manufacturers, also have a significant cost impact. The methodology takes the latter into account in 3 different ways, while the running repairs (due to their unpredictability) are not taken into account:

— The operator carries out all maintenance interventions throughout the life of the bus and coach;
— The purchase cost includes the costs of planned preventive maintenance or warranty period (so that the operator does not incur the costs) for a certain time (4–6 years), as specified in the sales contract, within the so-called warranty period, but the operator of the vehicles bears the cost of materials for running repairs;
— All maintenance tasks are carried out by a contractor independent of the operator, under a maintenance contract, throughout the life of the bus or coach or after the end of the warranty period.

The methodology distinguishes drive modes for maintenance but not powertrains within them, assuming that the lifetime and capacity of the energy storage used do not affect the cost values, mainly technological ones, resulting from the maintenance operations mentioned above. Moreover, as maintenance practices differ across Europe, the duration data can be parameterised as follows (24):

$$C_{k\ total,j} = \sum_{j=I}^{VI}\sum_{n=1}^{m} D^n * N_j * \begin{cases} c_{k,j,\alpha} & ,if\ c_{k,g,j} + c_{k,j,sz} = 0 \\ c_{k,g,j} + c_{k,j,sz} & ,if\ c_{k,j,\alpha} = 0 \end{cases} \quad (24)$$

Other costs and subsidies comprise the costs and subsidies for one-off or ongoing operations and tasks in the operation of buses and coaches which cannot be included in the above categories, such as:

— The annual vehicle tax burden;
— Compulsory and CASCO motor insurance;
— Other materials necessary for propulsion (e.g. lubricant, engine oil, window washer fluid), including AdBlue additive in the case of diesel propulsion;
— The cost of building the refuelling infrastructure, with two financing schemes (z = 0 one-off cost; z = 1 under a lease contract).

It should be noted that, as with maintenance costs, the methodology only differentiates between powertrains, as powertrain configurations do not significantly affect these costs (25).

$$C_{e\ total,j} = \sum_{j=I}^{VI}\sum_{n=1}^{m}(D^n * N_j * (c_{j,ga} + c_{j,biz} + c_{j,lub.})) + C_{j,refuel,z}\begin{cases} z = 0 \rightarrow C_{j,refuel} \\ z = 1 \rightarrow C_{j,refuel,1} * n * D^n \end{cases} \quad (25)$$

By summing up the above costs (and subsidies) according to the methodology, the total cost of the fleet of vehicles to be operated – as reported by the operator – throughout the public service contract can be calculated (26). In addition to the costs, the amounts of subsidies due or received for the performance of each task have been taken into account.

$$C_{total,j} = C_{price,j} + C_{loan,j} + C_{energy,j} + C_{k\ total,j} + C_{e\ total,j} - B_{aid,j} \quad (26)$$

The unit cost per kilometre is calculated by dividing the annual mileage by the annual mileage (27).

$$c_{unit,j} = \frac{C_{total,j}}{\bar{L}_j * n} \quad (27)$$

The different types of financing described in the methodology can be combined as desired (e.g.one sum at one time purchase, but outsourced maintenance and battery pack replacement with credit agreement). The methodology offers a tool in order to select the most efficient solution from an economic point of view, regardless of the organisation in charge of the procurement.

The cost value calculated by the methodology for different shoots can be used in two ways (*Figure 3*):
- In order to validate the cost data and the level of funding from the client, which are included in the statutory annual report that the service provider is required to draw up;
- The specific cost values of buses with different propulsion systems are “benchmarked” against each other in the context of sustainable public transport.

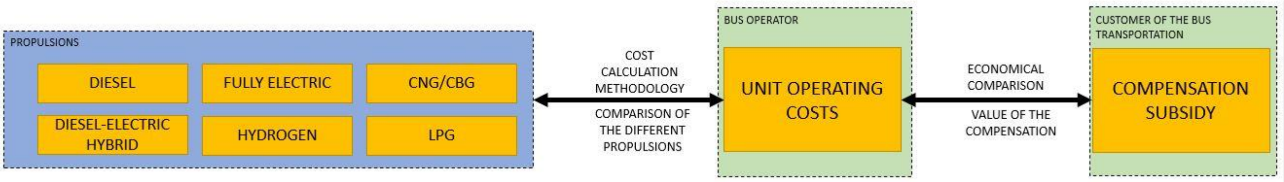

Figure 3 – Methodology for using unit operating costs (own edition)

The complex calculation methodology allows the determination and comparison of the unit operating costs of different bus transport modes over time, thus clarifying the compensation demand of the local or interurban public transport operator to the customer and minimising the economic risk for the bus and coach transport operator.

3. RESULTS AND CASE STUDY

The methodology was applied to the local bus public transport systems of two Hungarian municipalities: Paks, or Gödöllő.

We assumed a 10-year public service contract (the maximum time period of European Regulation). Based on the inflation value of the last 10 years and the MNB’s forecast, the discount rate is 6%.

Paks is a town of 20 thousand inhabitants located about 120 kilometres south of the capital of Hungary, Budapest. The municipality-owned Paks Transport Ltd. provides local bus transport on seven routes, with 10 100% electric buses since 1 February 2021. The Solaris Urbino 9.5 (midi) buses (4) have a battery capacity of 200 kWh, while their solo (Solaris Urbino 12) counterparts (6) have an energy storage capacity of 250 kWh. Based on the manufacturer’s energy consumption measurements (SORT-2), the former has an average energy consumption of 0.74 kWh/km and 0.85 kWh/km. These values closely approximate the real energy consumption values, since the measurement (made by the bus operator) data – depending on the weather, topography and traffic conditions – shows energy consumption values 0.7–1 kWh/km. The vehicles cover approximately 490,000 kilometres per year (assuming an even distribution with efficient operation: 49,000 km per bus). The buses, including the recharging station, cost €4.7 million, financed by the European Union (ICOP Plus). The purchase cost of midi size buses was €400,000/bus, while the solo version costed €450,000/bus. It should be noted that Volánbusz Zrt., as well as service providers in several other cities, have purchased purely electric, solo buses (Mercedes-Benz e-Citaro, BYD K2UB and K2UD, Ikarus e120) in recent years, the purchase cost of which was approximately €500–520,000/bus. The purchase price of electricity is €0.5/kWh. The cost of maintenance of the vehicles was €6,000/bus/year, based on the 2022 accounts, of which the bus manufacturer will take on a €1,000 per year warranty repair share for four years. The cost of insuring the vehicles is €1,000 per bus per year. The battery packs in buses are recommended by the manufacturer to be replaced every eight years (based on 90% availability of the vehicles and the turn-around time, this means about 3,100 charging life cycles) [27], [28].

Applying the methodology to the above data (for a lump sum vehicle purchase, using the above powertrain mix, assuming a 10-year public service contract), the $c_{unit,j}$ is calculated at €3.85/km. From the report available as public data, the cost of operating the buses in 2022, excluding the amount for payroll, is €1.82/km.

Gödöllő is located in central Hungary, about 20 kilometres east of Budapest, with a population of 32 thousand. Local public transport is provided by the state-owned MÁV Személyszállítási Zrt. on behalf of the municipality, currently on a compulsory basis, with five diesel-powered Credo Econell 12 solo buses. The vehicles cover 230,000 km per year (46,000 km/bus assuming an even distribution) on the 12 routes of the city, with an average fuel consumption of 33 litres/100 km. The five buses purchased by the public transport company in 2019 at a cost of around €160,000/bus did not require any infrastructure intervention (e.g. replacement of fuel tanks). The maintenance cost of the vehicles, based on the 2022 accounts, was €8,080/bus/year, which did not include any warranty operation on the manufacturer’s part. The bus company purchases diesel energy at a wholesale price of approximately €0.13/kWh [29], [30].

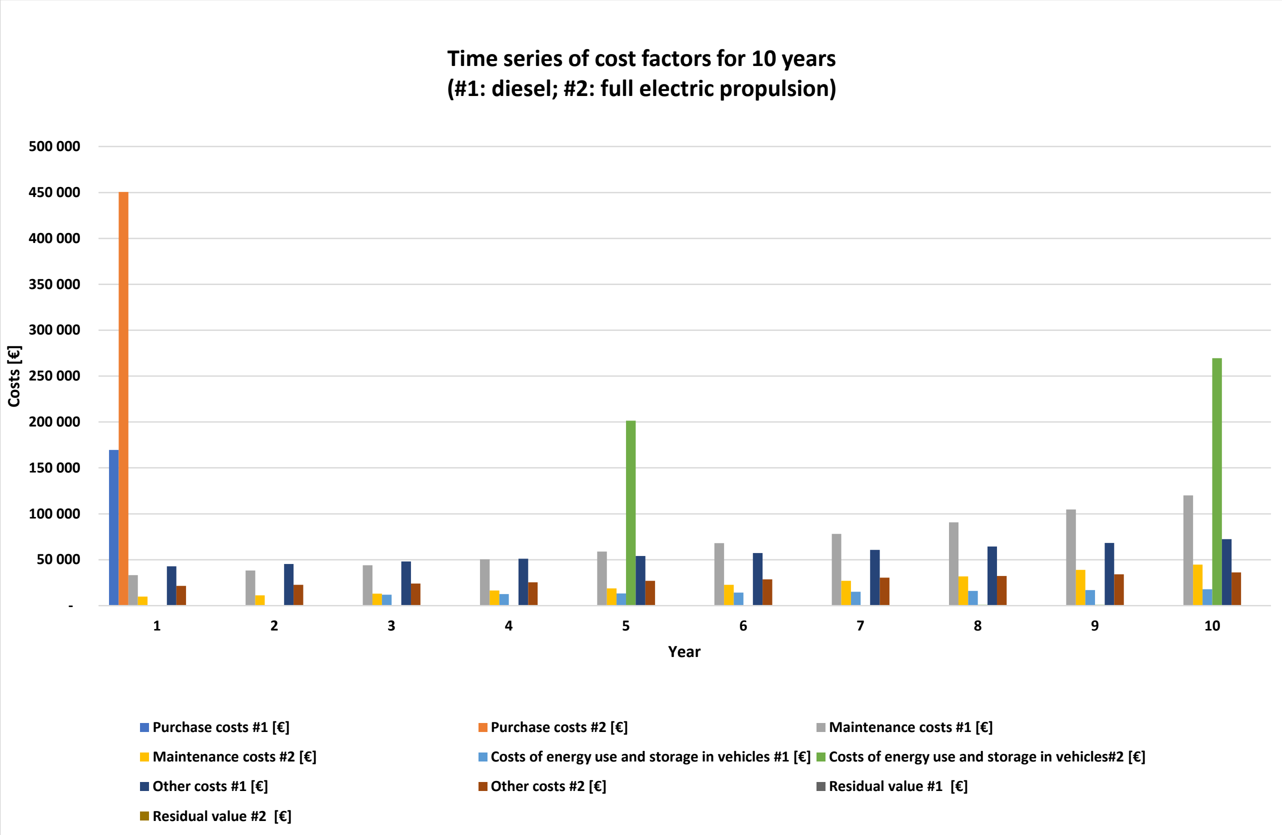

Figure 4 – Cost factors for diesel versus full electric buses (own edition)

Applying the methodology to local transport in Gödöllő, a new public service contract (due in 2024) for a market-based operator ($c_{unit,j}$) 2.05 €/km for diesel and 3.85 €/km for pure electric bus services, it would be economically viable to maintain the transport service for ten years (*Figure 4*). In 2022, this transport company would operate its vehicles for a fee of 0.99 €/km (excluding human resources and other costs necessary to maintain the service).

4. DISCUSSION

The unit cost values calculated using the methodology are as follows:

— Choosing the economically ideal propulsion system and estimating the costs of alternative propulsion vehicles.
— The level of funding for public transport should be reconsidered irrespective of the powertrain.
— The cost differential between different propulsion modes can be significant.

Based on Hungarian law, it is up to local authorities to organise local transport in their municipalities. It is their responsibility to provide local public transport in the most efficient [31], economically and environmentally sustainable way [32]. At present, there is no scientific study available in the Hungarian or international literature that could help local authorities to decide the parameters and powertrain of vehicles would be ideal from the above points of view.

Paks and Gödöllő are two cities in Hungary with a similar population and local mobility needs. The annual performance of the vehicles providing the service is also almost the same (46,000 vs 49,000 km/bus/year). The study carried out on the basis of the methodology showed that the use of pure electric buses increases the unit cost value. This is due to three reasons:

1) The battery life of pure electric buses is shorter than the service contract interval. The replacement of the battery packs is costly due to the current cost of storing 1 kWh of energy. A solution could be to reduce the contract interval, but then the procurement costs represent a higher unit cost.
2) The purchase cost of pure electric buses is much higher than that of diesel buses (around 1.5 to 2 times).
3) The recharging options for pure electric vehicles are currently still limited, so the procurement of these vehicles also requires the installation of charging infrastructure, which has entailed significant costs.

The studies carried out provide a picture of the economic aspect, but it should be stressed that environmental impacts may also need to be taken into account, as the social costs of pollutant emissions can make a big difference to the costs of maintaining a transport system. The examination of this and its incorporation into the methodology will be the subject of our next research.

It is important to highlight that the methodology allows the customer of the service to calculate the unit cost of the service using different alternative propulsion systems with different parameters. In this way, the developed transport system will work efficiently both from an economic point of view. Naturally – in addition to examined parameters in this case study – the analysis can be carried out with other propulsions (e.g. CNG, CBG, hydrogen) and with different vehicle parameters, however, due to the limitations of the paper, we dispensed with this.

It is also very important that the investigation carried out with the methodology highlights that the funding of local public transport, regardless of the propulsion, is currently not at the appropriate level. This is in correspondence with investigation by Al-Lami [33]. Under the current funding structure, only about half of the real operating costs are reimbursed to the operator, which is unsustainable for (mainly the market-based) bus operators. Until this methodology, in the absence of a scientifically supported study, bus operators and municipalities could only estimate their costs in the case of alternative propulsion vehicles. However, based on the methodology, it is possible to apply the appropriate financing volume. This is beneficial for the customer, since they have the opportunity to make decisions based on the real costs, and also for the service provider, since they can operate in an economically sustainable environment.

5. CONCLUSION

Today's economic and social challenges (e.g. energy crisis, inflation, labour shortages) also impact transport. These can be mitigated by creating sustainable and energy-efficient transport, including transport management, technology and industrial solutions. Much research focuses on the different options, but the combination of these options is less researched.

The present study combines the above tools by providing a methodology for comparing the operating costs of different conventional and alternative (pure electric, CNG, CBG, hydrogen, LPG) bus propulsion systems and by using these to highlight the specificities of the economic and operating environment and how to make the local bus transport system sustainable for the operator.

The methodology is based on a complex costing methodology, which considers the duration of the public service contract, including the discount rate and the operational (maintenance, energy use and storage, and other) costs. The methodology can be used to manage different forms of financing economically (e.g. lump sum or loan contract), as well as specific spare part replacements for each alternative propulsion bus, and to consider the most common maintenance strategies (e.g. planned preventive maintenance, outsourced maintenance).

The complex calculation methodology allows the economic impact of each mode of transport to be compared for any given period, thus allowing the customer to plan the compensation demand for local and interurban public transport and minimising the economic risk for the operator.

The operation of the developed methodology was demonstrated in the example of two Hungarian cities (Paks, Gödöllő).

The cost values calculated using the methodology show that, from an economic point of view, the operation of pure electric vehicles is financially not more advantageous over the whole contract period (10 years) than the operation of diesel buses. The existing capacities of buses (midi and solo) in both cases (Paks and Gödöllő) are replaced by the same passenger capacity and lengths, non-articulated (solo) buses.

On the other hand, it can be said that the accounting system and the economic operating environment, which are often used in local transport, are less attractive and profitable for the service provider, making the transport provision less sustainable and predictable. Although alternative propulsion vehicles have been found to operate with more favourable economic indicators, it is also paramount that transport companies receive adequate compensation for the service.

It has been shown that, irrespective of the propulsion system, only about half of the running costs of the vehicles are reimbursed to the bus operator by the customer. In addition, calculations based on the methodology have shown that the operation of pure electric buses has a higher financial cost. Based on the findings, using the methodology, both the service customer and the bus operator have the opportunity to gain an insight into the operating costs of buses with different propulsion systems and to rationalise the financing structure. As a result, the methodology can also function as a decision maker in transport planning and vehicle procurement.

The methodology, of course, can be applied as a comparison of all conventional and alternative bus services.

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Lakatos András, Tóth János, Török Ádám

Különböző alternatív hajtású autóbuszok összehasonlító elemzése fenntarthatósági szempontból

Abstract:
Napjaink gazdasági-társadalmi környezete számos problémával és kihívással néz szembe (pl. energiaválság, infláció, környezetvédelem), amelyek többsége kétirányú kölcsönhatásban van a közlekedési rendszerrel. A kutatók és az érintett szervezetek számos javaslatot és cselekvési tervet dolgoztak ki a „problémafelhő" mérséklésére az egyes közlekedési módok esetében, de ezek általában egy technológiai, gazdasági vagy ipari megoldásra összpontosítanak, nem pedig rendszerszinten kezelik a problémát. Ide tartozik az elektromos járművek vásárlásának és üzemeltetésének támogatása, a közösségi közlekedés használatának ösztönzése, valamint a lágy közlekedési módok fejlesztése. Ez a tanulmány egy többrétegű, komplex, költségorientált módszertant dolgoz ki a helyi és helyközi autóbusz-közlekedés fenntarthatóságának és gazdasági stabilitásának növelésére. A módszertan a különböző hagyományos és alternatív hajtású járművek főbb műszaki és üzemeltetési (karbantartási, energiafelhasználási és tárolási) paramétereire, valamint a rendelkezésre álló finanszírozási formákra épül, diszkontráta figyelembevételével. A

kidolgozott eljárás magyar városok példáival kerül illusztrálásra a különböző hajtások kilométerenkénti fajlagos költségeinek meghatározásával. A módszer segítségével támogatható a közlekedési szolgáltató és a megrendelő a gazdaságilag leghatékonyabb és legfenntarthatóbb hajtás kiválasztásában, egyúttal reális kép adható a teljes élettartam költségekről.

Keywords:
alternatív hajtású autóbuszok; tisztán elektromos üzemű autóbuszok; dízelüzemű autóbuszok; kilométer alapú fajlagos költség; gazdaságilag hatékony helyi autóbusz-közlekedés.