DOI: 10.62897/COS2025.3-1.162

10-12, November 2025, Győr

LONG-TERM SUSTAINABILITY ASSESSMENT OF LOCAL PASSENGER TRANSPORT

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The viability of urban transport systems is a critical element of the liveability of cities and, consequently, essential for the sustainability of the city as a whole. Achieving long-term sustainability is contingent upon the utilisation of energy-efficient transport modes. The attainment of this objective is impeded by the absence of a suitable decision-making instrument. In the present study, we examine the theoretical foundations of developing such a tool through the energy consumption of transport modes. The study was the foundation for the creation of the Transport Energy Unit Index (TEnU). This index is a comprehensive metric that considers the energy demands of various transport modes, with a focus on individual user needs. The index can be used to determine the most energy-efficient transport mode between two points, thereby informing appropriate transport policy decisions for the development of public transport systems, i.e., ensuring the long-term liveability of cities. The present research is confined to the domain of local passenger transport.

1. Introduction

The sustainability of different transport modes is demonstrably associated with their respective energy consumption. In view of the limited availability of natural resources, the efficient use of energy is among the most significant issues for the future. Achieving efficiency is also a topic of scientific research because it is influenced by numerous factors, and efficiency itself can be interpreted from several perspectives and is also an economic problem. The intricacy of this subject is attributable to the fact that energy is utilised not solely in the direct transportation process, but also in its preparation, with the objective of ensuring transportation conditions. This is especially true in public transport, where the primary task of the state or municipality is to use public funds carefully, i.e., to provide the most efficient transport options. Optimizing the energy consumption of (urban) public transport is necessary, but this also depends on many circumstances. It is essential that the optimal mode of transport for a given travel distance, motive, and conditions (e.g., temperature, sun, rain, terrain, personal conditions, availability of modes, multi-person journeys, luggage to be transported) varies. In order to achieve this goal, it is necessary to examine whether there could be an indicator that can assist in transport planning by providing an image of the energy consumption of public transport vehicles per selected unit and thus providing decision-makers with a tool to develop an appropriate energy-efficient urban transport network. The objective of the present research endeavour is to examine this intricate yet pivotal issue with a methodical and systematic approach, thereby introducing a novel indicator that can be utilised to universally assess a diverse array of transport alternatives. This can assist decision makers, and in the future, special Decision Support Systems (DSS) can be developed to support the identification of optimal transport measures.

Nevertheless, the present study is subject to certain limitations, as the aspects of very different types of transport needs (e.g., urban versus long-distance journeys) are not always directly comparable. The research is constrained to the domain of local passenger transport; consequently, the modes of transport that can realistically be utilised for this purpose are examined. This encompasses a wide range of transport modes, including walking, e-scooter, cycling, moped, car, bus, tram (LRT), train, and waterborne transport, along with their respective sub-variants. The structure of the paper is as follows. The purpose of Section 2 is to provide a comprehensive literature overview, which is intended to demonstrate the extant research gap that will be the focus of the research. The text goes on to discuss the formulation of the scientific problem, the hypothesis, and the expected results. The third section of this study outlines the research methodology. This is initiated with a definition of the research and modelling method, followed by a specification of the input data required for the model and the data collection needs of the various sub-sectors of transportation. Section 4 presents the results of the study, including the definition of the Transport Energy Unit (TEnU), and provides an analysis of the output data according to different sub-sectors. In light of the findings outlined above, the subsequent discussion in Section 5 will address the disparities in energy consumption among various transport modes, employing the TenU framework as a methodological foundation. In addition, the validity of the hypothesis is examined. Ultimately, proposals for the long-term sustainability of local passenger transport are formulated. The conclusion of the paper highlights the results and determines further research directions.

2. Literature review

The sustainability of transportation has become one of the most significant urban and environmental policy issues in recent decades. The foundation of approaches to sustainable transportation lies in the precise definition of the concept itself. Patlins (2017) emphasizes that establishing a clear definition of "sustainability" is a prerequisite to developing indicators that support the long-term development of public transportation. Miller's (2014) PTSMAP framework integrates the environmental, economic, social, and operational dimensions, thereby enabling a systems-based interpretation of decision-making processes. A congruent integrated perspective is posited by Li et al. (2015), who consider the alignment of technology, planning, and policy to be of pivotal significance.

The effectiveness of urban transport policies has a significant impact on emissions, congestion, and energy consumption. May (2013) provides a comprehensive analysis of the integrated application of demand and supply management, while Sun et al. (2021) use the example of Beijing to demonstrate how complex regulatory tools, such as emission standards, traffic restrictions, and electric vehicle subsidies, can contribute to reducing air pollution. Tafidis et al. (2017) observe a discrepancy between strategic documents and practical outcomes, while Hassan et al. (2022) emphasise the emission-reducing role of nuclear energy and technological innovation. Xue et al. (2017) posit that public-private partnerships (PPP) have the potential to engender financial efficiency and reduce CO2 emissions, contingent on the presence of a conducive regulatory environment. Poudenx's (2008) study emphasizes that integrated policy packages are more effective than isolated solutions. In the context of economic evaluation of transportation systems, consideration of both hidden and external costs is imperative. As asserted by Litman (1996), the prevailing pricing mechanisms are observed to be conducive to the promotion of automobile usage, thereby exerting a substantial environmental strain. Based on the indicators of Zheng et al. (2011), lower car dependency and a diversity of mobility modes result in a more favourable economic sustainability profile.

The measurability of sustainability is a prerequisite for effective policy intervention. Reisi et al. (2014) and Jeon et al. (2013) analyse the applicability of various indicators, while Dobranskyte-Niskota et al. (2009) conduct a quantitative comparison between EU member states using JRC software. Heidari et al. (2023) utilised Interpretive Structural Analysis (IPA) to demonstrate that in Tehran, the performance of numerous key indicators falls short of expectations. In their 2020 publication, Corlu et al. present computational methods for energy optimisation, with a particular emphasis on the role of artificial intelligence. Ngossaha et al. (2017) utilise fuzzy MCDM techniques, while Miller et al. (2016a) introduce the PTSMAT framework, which combines multidimensional indices. Sukarno et al. (2016) conducted an examination of energy consumption and emissions from transportation in an Indonesian city. This was achieved by developing a system dynamics model to project long-term trends. The study emphasises that the rise in private vehicle numbers is the primary factor contributing to rising emissions. Sultana et al. (2019) emphasise that disagreements frequently emerge between economic, social, and environmental objectives, underscoring the imperative for the identification of compromise solutions. Karjalainen and Juhola (2019) introduce the PTSIL framework, a tool designed to assess the sustainability of public transport by integrating economic, environmental, social, and governance aspects. A comparative analysis of Helsinki and Toronto reveals that, while overall progress is similar, differences in specific indicators reflect distinct regulatory and urban planning contexts.

The act of walking is considered to be a sustainable form of transport, with well-measurable energy requirements. Bastien et al. (2005) showed that during loaded walking, the metabolic cost per distance follows a U-shaped profile, with an optimum at a moderate speed that remains much the same even when moderate backpack loads are added. Waters et al. (1988) reported that oxygen uptake rises steadily with walking speed, yet the energy cost per metre is lowest at midrange speeds and climbs again when gait becomes very slow. Abe et al. (2004) discovered that carrying a modest load on the back—or even in the hands—can yield an energy-saving effect at slow speeds, but this advantage disappears once walking becomes faster. The advent of novel propulsion technologies has the potential to profoundly impact the sustainability of urban transportation. As Jing et al. (2022) demonstrate, the role of energy source composition is a salient factor in this field. Basso et al. (2024) revealed, through city-scale GPS analysis and physics-assisted modelling, that velocity, road gradient, passenger mass, and HVAC demand govern electricbus energy use in Santiago, providing a basis for prioritising routes in fleet electrification. Doulgeris et al. (2023) showed with field measurements and simulations in Athens that auxiliary heating-cooling loads are a dominant factor in battery-electric bus energy consumption, effectively limiting operational range despite sufficient traction capacity. However, it is important to note that this is subject to significant variation depending on factors such as route, passenger load, and the utilisation of climate control systems. In their study, Chang et al. (2019) examined the efficiency of hydrogen fuel cell buses. The researchers noted that the efficiency of these buses is also influenced by urban structural factors. They argued that urban forms and population density play a significant role in energy consumption and emissions. Dingil et al. (2019) provide empirical evidence that high population density is associated with reduced energy use, which is hypothesised to be a consequence of decreased car use. This assertion is corroborated by the findings of Shim et al. (2006) and Modarres (2013), who conducted research on polycentric urban structures and the repercussions of social inequalities. As Lefèvre (2009) emphasizes, integrated urban planning is of particular significance in the context of developing countries. As posited by De Gruyter et al. (2017), dense urban areas demonstrate superior sustainable transportation indicators, a phenomenon particularly evident in Asia and Latin America.

Transportation is not merely a technical issue; it is also a profoundly social one. As Miller et al. (2016b) assert, it is imperative that social, environmental, and economic factors are addressed in an integrated manner. Mattioli (2016) has examined the social construction of mobility needs within a new theoretical framework, emphasizing that technological innovations alone are insufficient. As highlighted by Velasco Arevalo and Gerike (2023), the specific characteristics of Latin America are often not taken into account by existing assessment frameworks, which are not aligned with the local context.

Despite the wide range of studies on sustainable transport, the literature reveals a clear gap: the absence of a unified indicator that enables direct comparison of different transport modes based on energy efficiency. Existing approaches often address environmental, economic, or social aspects in isolation, while integrated, decision-oriented tools remain limited. The analysed literature furthermore draws attention to the need to improve the efficiency of energy use in public transport, presents and analyses the energy demand of individual transport modes, but does not provide a uniform formula for comparing efficiency. Our research goal is therefore to develop a formula that enables the comparison of the energy efficiency of transport modes.

This study aims to address this gap by introducing the Transport Energy Unit (TEnU) — a novel formula that combines technical, operational, geographical, and user-attractiveness parameters. TEnU enables a comprehensive, energy-based evaluation of transport modes and serves as a practical decision-support tool for identifying the most sustainable options in local passenger transport.

3. Scientific Problem and Hypothesis

The extant literature suggests that sustainability constitutes the foundation for the long-term development of public transportation. Concurrently, it is acknowledged that the measurability of sustainability constitutes a necessary condition for effective political intervention. The analysis conducted revealed the absence of any indicator that would allow for a comparison of the various modes of transport in terms of energy efficiency. The creation of such an indicator is considered important, as it could serve as a guideline for decision-makers in adopting environmentally efficient transport solutions.

It is hypothesised that a general indicator can be defined – calculated on the basis of the energy consumption of different transport modes – which allows for comparison between them from a sustainability perspective. While the indicator describes transport modes, it is important to note that these modes are selected by individuals who perceive their value differently. Therefore, the attractiveness of the modes must also be represented in the model.

4. Methodology

TEnU is regarded as a decision-support tool that facilitates informed choices among various public transport modes. Consequently, a lower TEnU value is interpreted as more favourable. The calculation of the index is predicated on the grouping of characteristics of the transport modes, followed by the multiplication of the resulting base value by these grouped factors.

The base value is derived from walking, which is regarded as a universally available mode of transport. This base value is then multiplied by a set of parameters that are specific to each mode of transport. In order to ensure the comparability of the results, the outcome is divided by the transport performance measured in passenger-kilometres [pkm] that is characteristic of the given transport relation. This process leads to the determination of the TEnU value.
In order to facilitate the decision-making process regarding transport modes, it is imperative to consider the following factors:

- α= technical parameters
- β = operational parameters
- γ = geographical parameters
- δ = attractiveness parameters

The parameter α is indicative of the technical characteristics of the designated transport mode, including its capacity, velocity, and associated engineering attributes.

The β parameter encapsulates the organisational characteristics of operation, including the maximum number of passengers that can be transported within a given time unit (e.g., headway).

The γ parameter is principally concerned with infrastructure, including accessibility, length, usability (limitations), and topographical conditions.

The δ parameter is a metric that evaluates the mode of transport from the perspective of the individual. This encompasses attractiveness characteristics, which are the factors that influence a traveller's selection of a transport mode. These characteristics may include quality attributes, costs, and even weather conditions, among others. The δ parameter can be interpreted as a utility function; however, its value is contingent on the probability of certain factors occurring (e.g., rain), and is therefore best represented as a probabilistic variable. In this paper, however, the focus is on the case in which the individual is certain to travel. This means that the probability of the person not departing is excluded, and it is assumed that the act of travelling occurs with 100 % probability. In summary, the subject will travel between points A and B. However, the mode of transport selected may be influenced by external factors, such as meteorological conditions. For example, in the event of precipitation, the subject may opt for public transport, even for a short distance, as opposed to walking.

The subsequent stage in the methodology is to ascertain the weighting of each parameter in the calculation of TEnU.

The relationship between the performance, or in other words, perceived energy and speed of a given transport mode (1) can be described using the following second-degree polynomial (Bastien et al., 2005):

$$PE = a * v^2 + b * v + c \quad (1)$$

According to the formula, perceived energy consists of a component that depends on the square of speed, one that is linearly dependent on speed, and a constant term.

In accordance with the conceptual framework underpinning the analysis, TEnU is intended to denote the perceived energy consumption per pkm. The fundamental formula is as follows (2)

$$\mathbf{TEnU} = \frac{\mathrm{PE}}{\mathrm{P}} \quad (2)$$

where:

- PE = perceived energy consumption of the given transport mode
- P = passenger transport performance generated by the respective passenger flow [pkm]

This relationship must be weighted with the parameters described above to obtain an accurate representation of the utility of a given transport mode. In order to achieve this, it is assumed that a specific passenger flow is to be transported between points A and B over an s distance.

The parameters α, β, γ, and δ selected in our model correspond to the coefficients a, b, and c as follows:

- The technical parameters of the vehicle (α) have a dominant influence on performance and are therefore interpreted as coefficients of the quadratic speed term, i.e., α = a
- The traffic-related parameters of the transport mode (β) play a smaller role in determining performance and are thus interpreted as coefficients of the linear speed term, i.e., β = b
- The γ parameter describes the infrastructure characteristics, which are mode-specific but uniform across vehicle units, and are therefore considered constant: γ = c
- The δ parameter expresses the individual's relation to the given transport mode, which can be interpreted as a constraint or as a performance-reducing factor

According to previous studies and own experiences, the δ parameter is not constant, but rather is a function of distance and other factors (Figure 1).

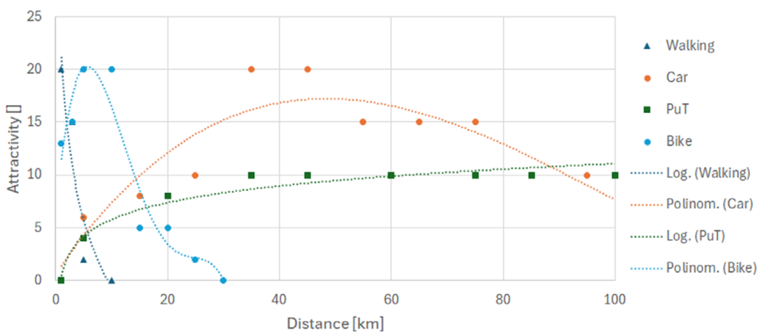

Figure 1: Attractivity in the function of distance

Based on all the above, the value of TEnU as a function of the speed of a given mode of transport can be interpreted as follows (3):

$$\mathrm{TEnU}_{sj}^{F} = \frac{a^{*}v^{2}+\beta^{*}v+\gamma}{\delta(s)^{*}P_{F}} \tag{3}$$

where:

- v = (average) speed of the given mode of transport

Furthermore (4):

$$P_F = F * s \tag{4}$$

where:

- F = passenger flow in the AB relation [passengers]
- s = distance between points A and B [km]

For the purpose of ensuring comparability between different transport modes, the individual TEnU values were plotted for each mode under varying F passenger flows and s distances (Figure 2).

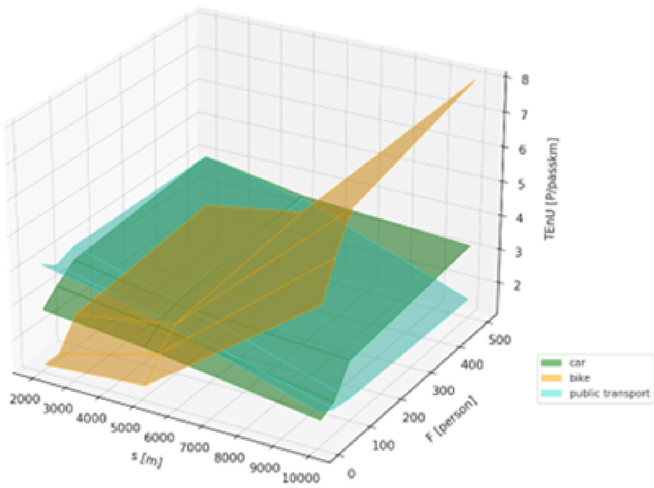

Figure 2: Possible values of TEnU in function of distance and passenger flow

Based on the resulting surface, bivariate functions (in F and s) can be formulated, for which local minima are sought. In accordance with the definitions of mathematical analysis, and by applying the substitution TEnU = f, the gradient vector of the function f is zero and is defined as (5):

$$\mathrm{grad} f = (f'_F(F_0, s_0),\ \ f'_s(F_0, s_0)) = (0,0)” \tag{5}$$

Furthermore, the determinant defined by the second partial derivatives must be greater than zero (6):

$$\begin{vmatrix} f''_{FF}(F_0, S_0) & f''_{Fs}(F_0, S_0) \\ f''_{sF}(F_0, S_0) & f''_{ss}(F_0, S_0) \end{vmatrix} > 0 \tag{6}$$

And additionally (7):

$$f''_{FF}(F_0, S_0) > 0 \tag{7}$$

If the values of F and s are known, the TEnU value corresponding to the transport of the given passenger flow between points A and B can be determined for each individual mode of transport. Based on these values, it can be assessed which mode of transport is the most environmentally friendly option for a given passenger flow and travel distance.

The TEnU value determined as described above does not only provide information about the most environmentally friendly mode of transport; due to the weighting introduced by the parameters, the utility of each mode is also taken into account. As a result, the most useful and environmentally sustainable mode of transport for the given relation (AB) can be identified simultaneously.

5. Discussion

Our results indicate that the appropriate choice of transport mode depends on the available speed and the level of emissions. The value of the α parameter has the greatest impact on achieving environmental goals; therefore, the reducibility of the TEnU (Transport Energy Unit) primarily depends on the technical characteristics of the given transport mode. In the case of walking, this is ideal since it does not produce harmful emissions. However, because of its low achievable speed, its effectiveness decreases significantly as the travel distance increases. This effect is reflected in the attractiveness of the transport mode.

The data also show that there is no single mode of transport that is clearly both the most environmentally friendly and the most useful; these two values vary depending on the route and the number of passengers. In short distances, walking proves to be the most beneficial means of transport. However, beyond that, various factors significantly influence which transport mode is optimal.

However, by calculating the TEnU, the preferred transport mode can be identified for a specific flow of passengers and travel distance. This is a limiting factor, as a city has countless passenger flows (travel demands) over a wide range of distances. However, using OD matrices appropriately constructed for transport planning, the environmentally friendly and efficient modes of conducting defined flows can be identified using this indicator. Based on this, a given transport mode can be developed, either through infrastructure construction or service improvement. Therefore, we consider the definition and use of the TEnU indicator to be useful from the perspective of sustainable urban transport, and particularly for public transport systems.

Our findings support the notion that the TEnU is suitable for comparing the sustainability of transport modes, which means that it can serve as a general indicator to evaluate the sustainability of transport based on energy consumption.

The research results also reveal certain trends. Long-term sustainable transport can only be supported by modes that have low TEnU values. To achieve this, we propose the following recommendations:

- Improve the technical characteristics of transport modes to ensure lower (ideally zero) pollutant emissions
- Integrate such environmentally friendly modes more widely into passenger transport.
- Increase the attractiveness of sustainable transport modes through service development (e.g. personalized availability via demand-responsive transport).
- Enhance economies of scale in capacity (either by adjusting carrying capacity or availability).
- Improve the accessibility of sustainable transport infrastructure (e.g., railway electrification, building a dense charging network, and using graph theory to strategically place charging points).

6. Conclusions

The viability of urban life is contingent upon the effective functioning of its fundamental systems. Transport is an inseparable aspect of urban existence, and the maintenance of the transportation network is a fundamental aspect of urban functionality. However, it is imperative to recognise that the operation of this system should not be regarded as an end in itself; rather, it is essential that it evolves towards and develops in the direction of sustainability.

In order to support sustainable transport, the present theoretical research introduces the Transport Energy Unit (TEnU) indicator. This indicator shows which transport mode requires the least energy between two points. TEnU is consequently an energy-efficiency-based evaluation instrument for transport modes, rendering it suitable for the assessment of the long-term sustainability of passenger transport.

In this article, the method for calculating the TEnU is defined, and its application to various transport modes is demonstrated. The utilisation of the indicator facilitates the selection of the most environmentally sustainable mode of transport for a specific relation. Consequently, TEnU functions as a decision support instrument, particularly for local governments, enabling them to formulate optimal transportation policy decisions, ascertain which transport modes to prioritise, and identify the necessary developments to facilitate sustainable transport.

The results of our research are theoretical; the practical applicability of the index requires further research. Our goal was to produce a decision-support tool that would enable the energy efficiency comparison of transport modes. We achieved this goal.

The utilisation of the index has the potential to contribute to the creation of a more liveable environment and the achievement of climate goals. The notion of green transport has been identified as a pivotal element in shaping the future of the sector, with the long-term energy sustainability of the sector being a crucial factor in achieving this objective, as well as the long-term sustainability of the liveability of cities.

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