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Modeling the Impact of Economic Interventions on Mobility Sustainability: A Multidimensional Approach

Economic instruments provide an opportunity to influence the sustainability of mobility positively. It is important to understand the distribution of mobility forms in terms of functional space use and individual and social utility to understand the effects of applying economic instruments. Economic instruments affect social utility by influencing individual decisions based on the technical characteristics of functional space use. This paper explores these relationships, which can help determine where and to what extent currently preferred economic instruments have an impact. The model allows for identifying areas where the use of financial instruments is expected to have significant utility. This article presents the details and internal connections of the developed four-dimensional model. The created model is a suitable tool for more accurately assessing the effects of economic instruments in the future.
Keywords: Economic Instruments, Sustainable Mobility, Personal Utility, Social Utility, Functional space use
JEL code: R11, R41, R48

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Introduction

Mobility development is one of the cornerstones of human development, shaping societies and economies. At the beginning of the third millennium, mobility transformation is driven by technological innovations, sustainability demands, and changing social expectations. Key aspects of this transformation include cognitive mobility, functional space use of mobility, various forms of mobility, sustainability demands, and economic instruments influencing mobility. Understanding these aspects and their internal connections can help achieve maximum results with economic instruments (Kocziszky, 2022).
Cognitive mobility integrates artificial intelligence (AI) and cognitive technologies into transportation systems (Horváth et al., 2024). This concept includes using AI to improve vehicle automation, traffic management, and user experience and developing and researching elements of the mobility system. Cognitive mobility aims to create seamless interaction between humans and machines, optimize routes, reduce congestion, and improve safety. For example, AI-equipped autonomous vehicles can make real-time decisions based on traffic conditions, increasing efficiency and reducing accident likelihood (Heinike et al., 2023). The advancement of cognitive mobility is crucial because it significantly increases our real-time knowledge related to mobility, allowing for more precise quantification of the effects of economic instruments (Zöldy & Baranyi, 2023).
The changes in society and mobility require us to examine and, if necessary, redefine our understanding of mobility. The classic urban-rural-highway mobility has changed with increasing urbanization, creating a new form of mobility space use: downtown mobility (Zöldy, 2024). This new approach more accurately describes reality and is crucial for evaluating the sustainability of road mobility tools and understanding the effects of related economic measures. Mobility needs and patterns vary significantly in different spatial contexts:

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Downtown mobility appears in densely populated city centres with many office workplaces, walking and micromobility (e.g., e-scooters, bicycles) are common due to short distances and high traffic congestion. Many areas have traffic-calmed or even car-free zones. Parking is scarce and expensive (Zamprogno & Esztergár-Kiss 2024). Public transportation systems such as buses and subways are essential for efficiently handling large numbers of commuters (Lang et al., 2024). Urban mobility is common in broader urban areas. Personal vehicles, public transportation, and micromobility options are used for the transportation, walking is less common compared to downtown. The availability of various transportation modes helps reduce congestion and provides flexibility for different travel needs (Crivellari & Retsch, 2022). In rural areas, personal vehicles dominate due to the lack of extensive public transportation infrastructure. Distances between destinations are generally greater, making walking and micromobility less practical (Infrastructure USA, 2017). Personal vehicles and freight transport primarily use highways for long-distance travel. Here, speed and efficiency are emphasized, with less focus on public transportation (Alessandretti et al., 2017).
Sustainability is a critical aspect in developing modern mobility systems (Zöldy et al., 2023; Zöldy et al., 2024). The transportation sector significantly contributes to greenhouse gas emissions, accounting for approximately 25% of global CO_2 emissions (Crivellari & Resch, 2022). To address this issue, there is increasing emphasis on developing sustainable mobility solutions such as electric vehicles (EVs) (Wengritzky, 2023), public transportation powered by renewable energy, and infrastructure for active transportation modes like cycling and walking. Policies promoting low-emission vehicle use (Lucyszyn, 2024), investment in public transportation infrastructure, and urban planning encouraging sustainable mobility are essential for reducing transportation's environmental footprint (Ghanbari et al., 2024; Attard & Ison, 2010).
Economic instruments play a vital role in shaping mobility patterns and promoting sustainable practices (Szalmáné et al., 2024; Zöldy & Kolozsi, 2025). These instruments can be categorized into two main groups related to pollution reduction (Hörcher & Tirachini, 2021). The first group includes "command and control" measures, while the second group encompasses "incentives," which cover a wide range of tools. Generally, incentive-based tools are more advantageous as they pay greater attention to economic efficiency. Additionally, implementation costs are typically higher for "command and control" policies (Rothengatter, 1994).
In summary, the development and transformation of mobility are driven by technological advancements, sustainability goals, and economic strategies. By integrating cognitive technologies, optimizing space use, promoting diverse forms of mobility, and utilizing economic instruments, a more efficient, sustainable, and inclusive transportation system can be created for the future.

Methodology

Main logic of the carried out research is presented in Figure 1. According to this hypothesis, economic measures primarily affect individual utility and functional space use of mobility. An example of a measure affecting individual utility is increasing the maximum allowed speed (reducing travel time by car), which increases the likelihood of choosing a personal car or supporting the use of shared electric scooters, which may increase their usage. A decision affecting functional space use includes supporting suburban rail passes or banning internal combustion engine vehicles from city centers. Economic measures rearrange individual decision preferences; through these choices, they affect the performance share of transportation modes influencing social utility and CO_2 emissions.

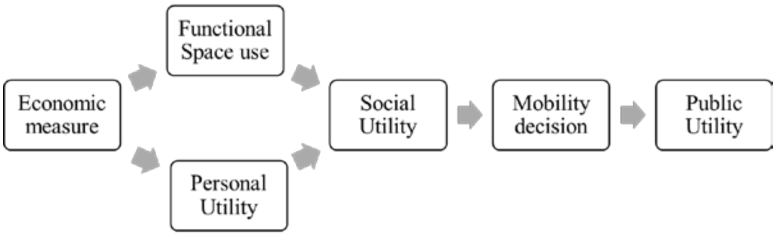

Figure 1: Mechanism of economic measures' impact on mobility
Source: Own compilation

Economic measures affecting mobility was summarised based on literature (Zöldy & Kolozsi, 2025). The paper analyzes economic policy tools aimed at promoting sustainable mobility. The study presents various economic tools used in the transport sector, such as regulatory and incentive-based tools. It reviews the European emission standards, technological standards, performance standards, as well as taxes and subsidies' role in promoting sustainable transport. The paper highlights the importance of economic tools in managing mobility sustainability and suggests ways to increase different tools' effectiveness.

During model creation, functional space use was examined based on a previously presented four-level model (Zöldy, 2024), distinguishing between downtown, urban, rural, and highway mobilities. The article examines changes in space use during the cognitive mobility era. The study presents urbanization's impact on transport forms and sustainability, analyzing current urban, rural, and highway categories, proposing a new category focusing on downtown areas, considering low speed, pedestrian interactions, and limited parking. It emphasizes the importance of adapting transport systems for sustainable mobility and highlights the need for further research in this area.

Individual utility means individuals choose transport options providing the greatest benefit or utility, comprising factors like travel cost, duration, comfort, safety, and environmental impact. Differing preferences result in varying utilities; for example, some prioritize speed, while others prefer cost-effectiveness or eco-friendly solutions. Thus, individual utility means selecting the best transport option matching preferences and needs. Literature shows travel time importance alongside cost equivalence. Travel time and cost equivalence, with travel cost usually being a flat rate, led us to choose average speed as the model basis.

Mobility decisions and alternatives, or modal split, represent the performance share of different transport modes in a given area or system. The modal split has four main elements: walking, micromobility, public transport, and car usage. Walking is the most sustainable mode, requiring no fossil fuel and having minimal environmental impact. It is influenced by sidewalk quality, pedestrian-friendly infrastructure, safety, and urban density. Cycling is also an eco-friendly mode, improving air quality and promoting a healthy lifestyle. It is influenced by the bike lane network, bike storage availability, safety, and comfort. Public transport, including buses, trams, metro, and trains, effectively reduces congestion and emissions. Its share is influenced by service frequency, reliability, comfort, cost, integrated ticketing, transfer options, and traveler information. Car usage is a convenient and flexible mode but has significant environmental impacts, including air pollution and congestion. Its share is influenced by fuel cost, parking availability and fees, tolls, and infrastructure quality.

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influenced by service frequency, reliability, comfort, cost, integrated ticketing, transfer options, and traveler information. Car usage is a convenient and flexible mode but has significant environmental impacts, including air pollution and congestion. Its share is influenced by fuel cost, parking availability and fees, tolls, and infrastructure quality.
The social utility of mobility decisions is significant in many aspects, as it affects not only individuals but also the well-being of society as a whole. The impact of economic measures on social utility appears in four major areas of mobility: environmental benefits, economic benefits, social benefits, and health benefits. Presented research focuses on examining the impact of economic instruments on sustainable mobility, equating social utility with this in our work. Among environmental benefits, we focus on CO_2 emissions, which drive current economic decisions.

Results

The dimensions presented in the methodology section form the framework of our model:

Dimensions

Based on the methodology section, the dimensions of the model were identified. These are shown in Table 1.

Table 1: Dimensions of the Mobility Sustainability Model

Dimension	Unit / Value Set
Functional space use	Downtown, Urban, Rural, Highway
Individual utility	Average speed, [m/s]
Mobility alternatives	Personal car use, Public transport, Micromobility, Walking
Social utility	Environmental impact, [CO_2/passangerkm]

Source: Own compilation

Simplification for Model Construction

During model construction, the relationships between dimensions were simplified to examine whether the model can be used to demonstrate and evaluate the effects of economic instruments. The simplification allows for demonstrating the operation, but higher resolution relationships will likely be needed in future model development.

Dimension Relationships

The relationships between dimensions were taken from international literature. When using the model, it is possible to specify unique dimension relationships, making the results more specific. At this stage of model creation, average relationships were applied to demonstrate the operation.

Table 2: Dimension Relationships in Mobility for Demonstrating the Impact of Economic Instruments

		distribution %	individual utility (average speed) (m/s)	social utility (CO_2 emission) (gCO_2/pkm)
Downtown	Public transport	34	5.5	80
	Personal car	25	8.4	160
	Micromobility	23	4	20

	Walking	18	1.42	40
Urban	Public transport	23	8.3	60
	Personal car	48	10	140
	Micromobility	16	6	20
	Walking	14	1.42	40
Rural	Public transport	7.65	13.9	60
	Personal car	77.5	19.4	115
	Micromobility	2.1	5.5	20
	Walking	13.1	0	0
Motorway	Public transport	5	7.7	76
	Personal car	95	30.5	140
	Micromobility	0	0	0
	Walking	0	0	0

Source: Own compilation

In Table 2, the dimension relationships were quantified based on international literature, the details are follows:

Functional Space Use Distribution

The distribution of passenger transport volume in passenger kilometers (passenger km) across different areas such as downtown, urban, rural, and highway can vary significantly by region and the data of the given year. As a starting point, the average mobility distribution of Europe was taken. The aggregated data in Table 3 were collected from multiple sources (ERF, 2024; Transportation Statistics, 2023; EEA, 2024; Eurostat, 2024; ITF, 2023).

Table 3: Distribution of Personal Mobility by Space Use (own collection)

Space Use	EU
Downtown	20%
City	40%
Rural	15%
Highway	25%

Source: Own compilation

Mobility Form Distribution

The distribution within each functional space was also determined based on international literature. For urban personal transport performance distribution, we used McKinsey's 2023 study (Heineke et al., 2023). The distribution of mobility in downtown traffic-calmed zones was determined based on sources (Oeschger et al., 2023; Schwinger et al., 2022). The rural usage distribution was based on (Purcher & Renne, 2005). For highway usage estimation, we used (Aparicio, 2016).

Determining Individual and Social Utilities

To determine the social utility of different mobility forms, we used (NAVIT, 2024) as a source for highways.

Diagram and Evaluation

The relationship between the examined dimensions is visualized in Figure 1. The x-axis represents individual utility, shown as average travel speed [m/s]. The higher the value on this scale, the greater the utility for the individual. The y-axis shows social utility represented by CO_2 emissions per passenger kilometer [gCO_2/passangerkm]. For society, greater utility means lower values on this scale: lower CO_2 emissions per passenger kilometer. The vertical z-axis represents functional space use: downtown, city, rural, and highway. In this space, personal transport mobility forms (walking, micromobility, public transport, personal car use) are illustrated. The sum of the shares in each functional space is 100%. The values of mobility forms are connected for easier visual understanding, indicating that they are of the same type, but their connection is not mathematically justified as they are not continuous.

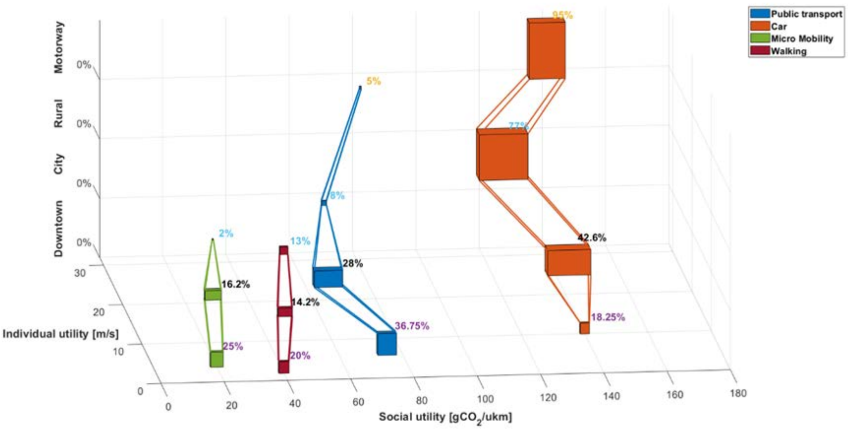


Figure 1: Visualization of the Relationship Between Examined Dimensions
Source: Own compilation

The initial state was developed using average values typical for a mid-European country. These values are suitable for demonstrating the relationships.

Demonstrating an Impact

With the completed model, the goal is to demonstrate, model, evaluate, and plan economic instruments that aim to influence mobility sustainability. For this demonstration, the introduction of the London Congestion Charge (LCC) in 2011 was chosen. According to (Tang, 2021), the charge boundary is drawn around the city center to alleviate congestion on London's busiest roads. The charge for entering the zone was initially £5 on weekdays between 7:00 and 18:30, which has since increased to £15. This Pigouvian tax forces drivers to internalize the externalities imposed on others by congestion. By closing the gap between the marginal cost of driving and the social marginal cost, the LCC reduces equilibrium traffic volume, bringing it closer to the socially optimal level. The introduction of the LCC has the following impacts, quantified in Table 4:
In the downtown area, the cost of personal car use increases, reducing its share. CO_2 emissions per passenger kilometer decrease due to faster flow, reduced idling, and less slow parking search. The shares of the other three mobility forms increase.

In the city, the share of personal cars slightly decreases, average speed increases, and CO_2 emissions per passenger kilometer decrease, improving social utility.

Table 4: Demonstrating the Impact of Economic Instruments in the Model

Downtown congestion price		distribution %	individual utility (average speed) (m/s)	social utility (CO_2 emission) (gCO_2/pkm)
Downtown	Public transport	36.75	6.05	75
	Personal car	18.25	10.08	140
	Micromobility	25	4	20
	Walking	20	1.42	40
Urban	Public transport	28	8.715	58
	Personal car	42.6	10.5	135
	Micromobility	16.2	6	20
	Walking	14.2	1.42	40
Rural	Public transport	7.65	13.9	60
	Personal car	77.5	19.4	115
	Micromobility	2.1	5.5	20
	Walking	13.1	0	0
Motorway	Public transport	5	7.7	76
	Personal car	95	30.5	140
	Micromobility	0	0	0
	Walking	0	0	0

Source: Own compilation

The initial state was developed using average values typical for a mid-European country. These values are suitable for demonstrating the relationships.
The changes between the initial state and the introduction of the congestion charge are shown in Table 5, and the modified Figure 2 based on the data from Table 4.

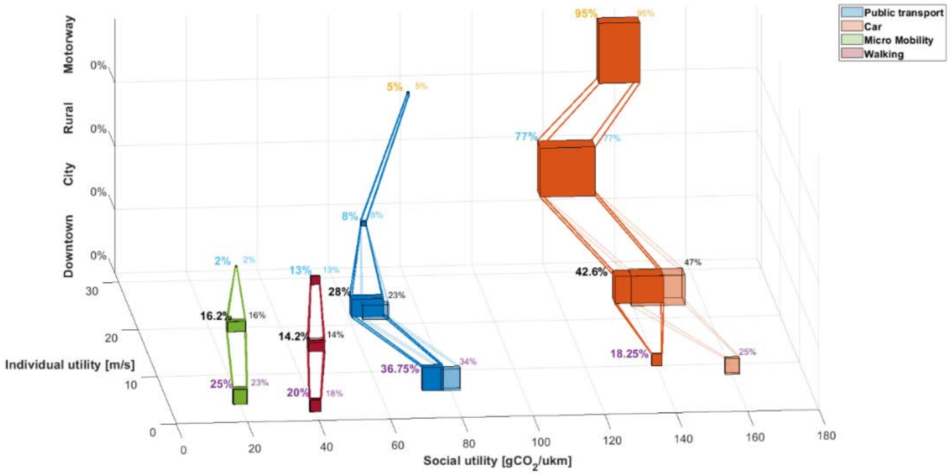
Table 5: Changes Caused by the Introduction of the Downtown Congestion Charge

Downtown Congestion Charge		Distribution change %	Individual utility (m/2s)	Social utility (gco2/passkm)
Downtown	Public transport	2.75	+ 0.55	-5
	Personal car	-6.75	+1.68	-20
	Micromobility	2	0	0
	Walking	2	0	0
Urban	Public transport	5	+0.415	-2
	Personal car	-5.4	+0.5	-5
	Micromobility	0.2	0	0
	Walking	0.2	0	0

Source: Own compilation

The introduction of the London Congestion Charge generates an average annual revenue of £200 million for the city, improving social utility. The model shows that it effectively intervenes in the mobility system, shifting it in a direction more favorable to society. It increases the individual and social utility of personal cars while reducing their share in favor of more socially beneficial forms of mobility, primarily public transport. The social and individual utility of public transport improves as a result of the measure.

Figure 2: London congestion charge effect



Source: Own compilation

The example demonstrates that the model works and is suitable for presenting the impacts of economic measures on mobility.

Further Development

In further developing the model, we aim to create connection points where data available in existing databases can be integrated into the model. The goal is to enable more precise analysis of the impacts of economic measures on mobility by filling the general model with specific data for a country or region. Further refinement of the model will involve creating the possibility for more detailed connections between dimensions, rather than point-to-point connections. At this stage, it is important to consider the accuracy and resolution of the data available for application and to provide the option to return to an aggregated level. Part of the model's development includes analyzing already implemented economic measures and comparing the results with those from other sources.

Conlusion

In our work, we examine the impact of economic instruments on mobility sustainability. The goal of our research is to develop a four-dimensional model that helps identify the effectiveness of economic instruments in different mobility forms and spatial contexts. The methodology is based on analyzing functional space use of mobility, individual and social utility, and mobility alternatives. The results were validated through an existing example. The model is suitable for demonstrating the impacts of economic instruments, such as the downtown congestion charge. Further development of the model will involve integrating existing databases and refining dimension connections.

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