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A fuzzy hybrid approach to investigate commuter satisfaction in Central Europe

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ABSTRACT

Commuter satisfaction with their chosen mode of transport significantly affects quality of life, well-being, and the sustainability of commuting practices. This study uses a fuzzy-hybrid TOPSIS approach, applied to data from seven functional urban areas in Central Europe. The method effectively creates a composite indicator for assessing satisfaction levels by considering factors such as socioeconomic conditions, geographical features, and mobility-related data. The research analyzes how satisfaction varies according to these factors. Results indicate that commuter satisfaction levels vary across different factors, including age, education, occupation, gender, travel distance, travel time, commuting cost, and income. Notably, those with shorter commuting times and lower expenses tend to report higher satisfaction, while unemployed and low-income commuters, as well as those using active modes of transport, often express lower satisfaction levels. Interestingly, bus riders find their trip more satisfactory than car drivers, but train commuters are the least satisfied of all. Overall, this study provides valuable insights into commuter satisfaction, informing the development of policies and strategies to improve the transport infrastructure and services and promote the choice of sustainable modes.

1. Introduction

Commuting, which involves traveling to work or school, is a common aspect of daily travel and can be performed through various modes of transportation, such as private vehicles, public transport (PT), and active modes (Pooley and Turnbull, 2000). Commuting can have negative impacts on the environment, quality of life, and sustainability (Dargay and Hanly, 2007; Lorenz, 2018; Cavallaro and Nocera, 2024). Studies by Giménez-Nadal et al. (2019; 2020) and Rodríguez-López et al. (2017) show that longer commuting times are associated with increased stress, sadness, self-consciousness, and fatigue during daily activities, while shorter commuting distances and times are associated with higher rates of active travel and lower stress levels. However, commuting behavior and modal choice are influenced by complex interrelated factors that need to be considered in transport planning and policymaking, such as income, safety, availability and quality of PT, and others (Jang and Ko, 2019). A poor understanding of these factors might result in car-centric commuting systems even in contexts where competitive alternatives are available (Handy et al., 2005). A large body of literature exists on the interrelationship between commuter preferences, transportation and planning policies, and the socio-economic and physical environment. In the context of mode choice analysis, it is common to frame the work within the utilitarian theory of travel (Currim, 1981). Typically, discrete choice models are used in these analyses. These models are consistent with the utilitarian theory by capturing the probabilistic nature of decision-making and estimating the likelihood of choosing a particular mode based on its attributes and traveler characteristics (Sinha and Labi, 2011). Commuter satisfaction is a less frequently discussed topic. Similar to mode choice analysis, it is often approached using discrete choice models, although several other methods have recently emerged (Section 2). However, these approaches require the availability of large datasets and can make comparisons across different geographic, socioeconomic, and political contexts a challenging task, especially when seeking statistically relevant results in a subset of mode choice analysis, such as the study of commuter satisfaction (St-Louis et al., 2014). This paper overcomes this problem by employing a Fuzzy-Hybrid TOPSIS (FHT), a novel approach in the field, which is able to preserve the integrity of the datasets and ensure comprehensiveness and thoroughness. The study compares seven Functional Urban Areas (FUAs; Eurostat, 2018) in Central Europe and

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focuses on understanding commuter satisfaction through the construction of a composite indicator. It then analyzes how several socio-demographic variables, such as age, gender, education, occupation, travel distance, travel time, modal choice, and income, influence commuter satisfaction. Additionally, the analysis allows for preliminary investigations into the correlation between satisfaction and mode choice.

For this purpose, this paper uses a survey designed within the EU-funded project Smart-Commuting (Fig. 1), designed to gather a common overview of commuter socioeconomic conditions and modal choices and link these to the overall availability of transport options and the local policy framework.

The case study FUAs are located in Italy (Rimini), Slovenia (Koper and Velenje), Croatia (Zadar), Austria (Weiz), Czech Republic (Hranice), and Hungary (Szolnok), thus providing a diversified framework (see Section 3) and a composite case study. The analysis of commuter satisfaction across Central Europe through the FHT approach is expected to provide useful insights into effective policies to promote sustainable modes for systematic mobility. This is achieved through an innovative methodological approach in this domain, the FHT model, addressing two key research questions: first, which individual socio-economic and travel-related determinants have the most significant impact on commuter satisfaction in Central Europe? Second, which aspects of commuter satisfaction are most relevant in informing policy decisions aimed at promoting sustainable commuting choices and influencing commuter behavior?

The rest of this paper is structured as follows: Section 2 is a literature review on the determinants of commuter mode choice and satisfaction. Section 3 presents the materials, Section 4 details the methodology, Section 5 highlights the results, and Section 6 is the discussion, summarizing the main findings and policy implications. Finally, Section 7 concludes the paper.

2. Literature review

Various territorial and socioeconomic conditions and the availability and quality of transport options influence commuter mode choice and satisfaction. Individual preferences are shaped by living and working conditions, with factors such as travel time, trip cost, and compatibility of working hours with PT schedules playing significant roles. Numerous studies have examined the determinants of modal choice for commuting trips over the past decades (Ha et al., 2020). Traditionally, research on mode choice has relied on discrete choice models, rooted in the random utility framework (McFadden, 1981; Hillel et al., 2021). These models generally assume that individuals are rational agents seeking the greatest utility, with utility being a function of individual features and stochastic terms (Cappelli and Nocera, 2006; Zhang et al., 2023). However, the non-linearity and heterogeneity between attributes influencing commuter choices are increasingly recognized. Mixed approaches have been explored to improve discrete choice models' ability to identify non-linear relationships. For example, Ding et al. (2021) use a semi-parametric multilevel mixed logit model to investigate the link between the built environment and transit use in Nanjing, China. Machine learning is also gaining recognition for its ability to capture non-linear relationships in mode choice decisions. Hillel et al. (2021) provide a systematic review of machine-learning methods for modeling passenger mode choice, finding that machine-learning models have significantly higher predictive accuracy than traditional multinomial and mixed logit models. Despite their predictive accuracy, machine learning models sometimes produce behaviorally unreasonable arc elasticity and marginal effects (Zhao et al., 2020). Alongside machine learning, artificial neural networks have recently been used to predict mode choice. Ma and Zhang (2020) introduce entity embedding to enhance deep neural networks' predictive power by automatically learning the representation of categorical variables in vector spaces.

Fig. 1. Location of FUAs participating in Smart-Commuting within European countries belonging to the Central Europe programme area (dark grey).

Moving away from the more purely methodological aspects of the debate, the following subsection provides an overview of the impact of the main determinants on commuter mode choice, particularly focusing on the choice to drive and on linking the socioeconomic and travel-related determinants of mode choice for commuting to commuter satisfaction. We then propose a focus on the determinants of commuter satisfaction.

2.1. Determinants of commuter mode choice

De Witte et al. (2013) identify four groups of mode choice determinants, namely travelers' socio-demographic characteristics, spatial environment, trip attributes, and socio-psychological factors. They find that car availability, income, age, household characteristics, and density are the most often studied and significant factors. Besides the availability of specific transport modes, which limits commuter choices, the traveled distance significantly affects modal choice, with increasing distances corresponding to a lower use of non-motorized transport (Lawson et al., 2013). Especially for commuting trips, travel distance and time are highly valued by travelers. In a study for the Puget Sound region (around Seattle), Frank et al. (2008) find that travel time of different modes is a significant predictor of mode choice, with commuters being more sensible to travel time than trip costs. Generally, commuters are also influenced by the ratio between travel time by any alternative or car, with lower time savings via driving corresponding to a more likely choice of alternatives (Chakrabarti, 2017). Commuting distances and travel time are deeply linked to the territorial and anthropic morphology of the city (Zhao et al., 2018). High population density, job-housing balance, mixed land use, and access to public services are associated with lower car dependence (Cervero, 1996; Scorrano and Danielis, 2021). Based on their income, opportunities, conditions, and mode preference, individuals choose to live in neighborhoods with greater access to transport facilities and/or short distances to their work location (Charreire et al., 2021). Cao et al. (2009) link residential self-selection to commuter socioeconomic conditions and, thus, to their choices. Higher-income groups may work closer to home −thus being able to cycle or walk to work- or can afford homes in proximity of high-quality PT (Commins and Nolan, 2011; Christiansen et al., 2014; Braun et al., 2016). Lower-income individuals are instead either stuck with walking or biking to work (in dense communities where trips are short) or have no alternatives to resource-wasting drives from their suburban/rural residences to job-attractive areas. Education is linked to these aspects: highly educated people, normally considered more aware of the impacts of private motorized transport and keener to choose alternatives, are also often part of higher-income groups, further enhancing their opportunities and flexibility (Schwanen et al., 2001; Clark et al., 2016). Several *meta*-analyses are available on the link between the built environment, travel time, residential self-selection and mode choice. Interested readers can refer to Leck (2006) and Ewing and Cervero (2010) for further insights.

Commuter age is often studied with respect to the choice of active modes. Several authors find that commuters are more likely to use non-motorized transport as their age increases (Ayobami and Oladipupo, 2018; Zhao et al., 2018; Baquero Larriva et al., 2024). Other studies, however, find that young people are more inclined to cycle often (Fraser and Lock, 2011; Muñoz et al., 2016; Poliziani et al., 2023) or find non-linearity between age and mode choice. The evidence of the role of age in the choice of active modes for commuting is thus inconclusive, and often linked to health or safety issues (Scorrano and Danielis, 2021). A well-accepted conclusion is that in those countries with a high prevalence of cycling, like Denmark and The Netherlands, older age groups tend to cycle more, whereas the opposite trend is observed elsewhere (Hansen and Nielsen, 2014; Ton et al., 2019; Grudgings et al., 2021). More broadly, commuter age can be related to their willingness to pay and environmental concern. Circella et al. (2016), for example, find that young Americans drive less than their members of older generations for systematic trips. In general, however, commuters behave more like their peers of the same gender than their peers of the same age (Grudgings et al., 2021). This is particularly true for active modes. From a broader perspective, according to Miralles-Guasch et al. (2016), gender is a key aspect of modal choice. Bautista-Hernández (2021) reviews numerous studies from different global contexts, concluding that women are more likely to walk and have a more restricted array of possible and convenient solutions available for their needs. Consequently, women generally travel less than men and for shorter distances but spend more time on their commute (Miralles-Guasch et al., 2016; Lecompte and Juan Pablo, 2017). Moreover, they rely less than men on private cars, especially in lower socioeconomic areas and among the least wealthy groups (Gordon et al., 1989; Maciejewska and Miralles-Guasch, 2020). The gender gap in travel behavior and commuting has been intensively studied within the literature. Interested readers may refer to Hu et al. (2023) for further insights.

Shifting the focus to the individual reasons for a specific mode choice, Scheiner and Holz-Rau (2012) provide an effective synthesis by stating that each socioeconomic group's preferences, attitudes, habits, and even ecological norms, all lead to diverse travel outcomes. The convenience aspect in terms of cost-savings, which could be policy-driven, is considered among the most influential elements in the choice of active modes (Bergantino et al., 2021). As mentioned before, trip costs are generally considered less influential than travel time in determining the modal choice for anelastic trips such as the home-to-work commute; nevertheless, policy interventions on trip costs can be important in determining commuter modal choice (Forsey et al., 2013). Additionally, the low elasticity of commuter demand could result in commuters being unsatisfied with their modal choice, due to high costs, but perceiving an absence of feasible, more satisfying alternatives. This can be the case for commuters choosing private cars, categorized as either car-dependent or car users. The former have no alternative to driving, while car users have alternatives but choose to commute by car (Dashtestaninejad et al., 2023; Gardner and Abraham, 2008). The built environment is widely recognized as the most important determinant of car dependency for commuting, influencing the density of jobs and housing and thus travel time and costs (Leck, 2006; Yang et al., 2021). The physical and functional characteristics of the built environment and the morphology of society are closely linked within the residential self-selection paradigm, as people with different incomes and belonging to different social groups make (or are forced to make) specific choices about where to live and work. This in turn implies that car use for commuting is linked to all the other determinants discussed so far. However, scholars point to numerous contextual differences: where individual safety is a concern, such as in the megalopolises of developing countries, car ownership and use is perceived as a status symbol even by less affluent populations and by women, who often make up the majority of drivers (Ashik et al., 2024a). In Europe, on the other hand, it is often men who drive the most, and the likelihood of owning a car increases in proportion to household income (Berrill et al., 2024). It is agreed that the higher the car ownership rate, the higher the modal share of cars for commuting (Strading, 2016). Car dependency also increases with longer distances (Steg and Gifford, 2005), higher residential and lower employment densities (Dashtestaninejad et al., 2023; Ye and Titheridge, 2017), and household size: parents are more likely to drive compared to singles or couples (Clark et al., 2016). The role of education is less clear: typically, more educated people are more likely to use PT and active modes; however, this is not true in all contexts, as sometimes those with high education (likely, high income) make housing choices that involve long commutes (Berrill et al., 2024). In addition to environmental and socioeconomic determinants, drivers' choices are deeply influenced by behavioral and cognitive aspects, largely related to habits and perceptions of autonomy concerning the car (Stradling, 2016; Hoffmann et al., 2017). The topic of behavioral and cognitive aspects behind car use choices, including intentions, attitudes, perceived behavioral control, subjective, descriptive, and moral norms, habits, responsibilities, and environmental concerns, is too large to be discussed exhaustively here. We refer readers to *meta*-analyses by Gardner and Abraham (2008), Ewing and Cervero (2010), and Lanzini and Khan (2017) for further insights.

2.2. Commuter satisfaction

Travel satisfaction encompasses the emotions experienced during the trip and a post-trip cognitive evaluation. Unlike attitudes, which persist beyond the activity, satisfaction is a transient or enduring mood tied to the duration of the trip (De Vos et al., 2022). An extensive literature examines the relationship between commuter satisfaction and travel attributes, including mode choice (Ye and Titheridge, 2017; Guan et al., 2023). Other studies extend this framework to include the built environment and psychological factors such as attitudes. In most cases, the methods used to study satisfaction overlap with those used to study mode choice, relying largely on statistical analysis, discrete choice, and structural equation models. There are also studies framing systematic traveler satisfaction in agreement ratings of statements inspired by the Satisfaction with Life Scale (De Vos et al., 2022). These elaborate on the link between travel attitudes, desires, intentions, behaviors, and satisfaction based on various psychological theories in travel behavior research. More recently, objective physiological measures such as heart rate and facial emotion have also been used to study commuter satisfaction (Zhao et al., 2024). Ye and Titheridge (2017) find that short distances from home to work not only encourage active travel and reduce car use but also grant high satisfaction to commuters who walk or bike. In his review of commute satisfaction, Lunke (2020) finds that people with longer commutes systematically report lower subjective well-being and satisfaction, and that active commuters tend to be the most satisfied with their trips. PT commuters are generally dissatisfied with their trips, but mode-specific conclusions are not unambiguous. Indeed, other authors find that PT is a satisfying commuting mode, thanks to the possibility of proactively investing travel time (Olsson et al., 2013). The overall quality of PT service, including seat availability, reliability, and delays, has a strong impact on commuter satisfaction. Lunke (2020) provides conceptual background to these aspects and reports several studies establishing a link between commuter satisfaction, the psychological concept of Subjective Well-Being, and Quality of Life. He argues that Subjective Well-Being has a role in determining commuter travel behavior. The actual and perceived safety associated with the chosen mode plays an important role in commuter satisfaction (Majumdar et al., 2021). Some safety-related attributes, such as the presence of lighting or sidewalks, may be related to the built environment. People's satisfaction with their residential location influences travel-related satisfaction (De Vos et al., 2016). According to De Vos et al. (2013), many will accept a longer commute in exchange for a better job or residential location. This aspect is related to people's income –and thus opportunities- and the dynamics of residential self-selection. Low-income groups consistently report lower levels of commuting satisfaction (Ye and Titheridge, 2017). A mismatch between mode choice and travel attitudes (i.e., feeling "forced" to use certain modes) contributes to low satisfaction. Travel attitudes towards specific modes are associated with commuter satisfaction (Ye and Titheridge, 2019). Positive attitudes toward one's commute lead to higher commute satisfaction, a positive personality, and a better perception of one's lifestyle (Choi et al., 2021). In addition to individual preferences, people's attitudes are likely to be influenced by previous travel experiences and the travel patterns of their peers. For drivers in particular, personal preferences and peer experiences are determinants of both mode choice and satisfaction (Guan et al., 2023). De Vos et al. (2022) build on the theory of cognitive dissonance, stating that satisfaction is not only influenced by individual behavior and attitudes, but mainly by the alignment between the two. An individual's inability to travel in their preferred mode impacts their travel satisfaction and quality of life (De Vos and Singleton, 2020). Negm et al. (2024) find through a binary logistic regression model that both consonant and dissonant commuters have a high probability of satisfaction with their commute, except for dissonant car users. This implies that some commuters drive because they are – or feel – compelled to do so, even if they are not satisfied with driving. Understanding the reasons for the dissonance between mode and preference and its relationship to satisfaction is important for studying satisfaction and understanding how to facilitate a shift to sustainable commuting modes.

In the following sections, we propose the materials and an alternative method to study commuter satisfaction according to socio-economic and territorial factors, as well as the mobility alternatives available.

3. Materials

Smart-Commuting project developed Sustainable Urban Mobility Plans and studied systematic mobility throughout central Europe, namely in the municipalities and urban areas of Rimini (Italy), Koper and Velenje (Slovenia), Zadar (Croatia), Weiz (Austria), Szolnok (Hungary) and Hranice (Czech Republic) (Fig. 1, above). These are small and medium-sized FUAs (between 11,627 and 148,241 inhabitants) located both inland (Velenje, Hranice, Weiz, and Szolnok) and on the Mediterranean coast (Rimini, Koper, and Zadar). All FUAs are main regional attractors for commuting (Smart Commuting, 2020). Rimini, for instance, attracts commuters from 20 municipalities of 4 Italian regions and the Republic of San Marino; Hranice is the workplace for people from 25 municipalities, some of which are outside Czechia. Even some of the smaller FUAs, like Koper (53,292 inhabitants) offer many workplaces (24,500) thanks to the tertiary vocation (Koper itself, Rimini, Zadar) and/or to industry (e.g., Szolnok, Hranice, Velenje). The variability of the FUAs part of the case study poses methodological challenges. These challenges are addressed through the FHT approach, which effectively manages the vagueness and uncertainty typically present in the information extracted by questionnaires based on Likert scales (Lorkowski & Kreinovich, 2013; Kandasamy et al., 2020). However, it should be noted that despite the different criticalities, the FUAs have all joined the EU-funded Smart-Commuting project as they share common problems with relevant commuting movements that pose a challenge to local sustainability and quality of life. As part of the Smart-Commuting project, a survey was conducted in 2021 among a random sample of residents over the age of 15. Responses were collected through institutional platforms of the project partners and by the authors using interviews through informal online channels.

The questionnaire included socioeconomic and demographic questions, behavioral aspects, and questions specifically related to factors affecting modal choice. Fig. 2 illustrates the structure of the questionnaire, which is available in full upon request to the corresponding author.

3.1. Data description

The sample consists of 1,736 respondents, randomly chosen within the population, performing their commute in one of the seven involved FUAs. Table 1 shows the sample size of each group, considering the socio-economic information gathered from the questionnaire. Koper was the city with the least respondents (96), while Szolnok and Velenje were the ones with the highest sample numbering (339 and 303, respectively). The intermediate age groups (between 30 and 45 years and between 46 and 60 years) are the most numerous and together account for more than 76 % of our sample. There are more respondents with a high education level (41.13 %) and private sector employees (39.80 %). Furthermore, there are gender sample differences in the data, as our sample has a prevalence of women (56.16). Travel costs reflect out-of-pocket expenditures declared by commuters in the survey, thus including parking, fuel, tolls, and a share of maintenance and insurance costs. The survey did not require respondents to split these costs, although they were asked how much they needed to pay to park their vehicle at work/school.

Drawing on the concepts discussed in Section 2.6, commuter satisfaction is normally based on the cost, speed, and safety of the means of transport (Lunke, 2020). According to this framework, we analyze the respondents' satisfaction through four different specific criteria (Table 2). Respondents were given a rating scale in which they would respond with a score of 1 if they were not interested in transport alternatives, cost, and speed. Conversely, they would rate their interest as either 2 or 3 if they were somewhat interested. A rating of 4 indicated a great interest in these factors. In this sense, respondents most satisfied with their means of transport are expected to give a 1 to the lack of alternatives (C1), and a 4 to questions about cost (C2), speed (C3), and safety (also in connection with the possibility of COVID-19 transmission, given that the survey was administered in late 2021) (C4). Thus, to simplify future analyses, item C1 is reverse-coded.

Section 4 describes the fuzzy-hybrid TOPSIS model in depth, explaining its relevance to the study and how it integrates various socioeconomic and mobility-related factors to produce comprehensive results. Additionally, this section discusses the rationale behind selecting the sample from seven functional urban areas in Central Europe and outlines the steps taken to ensure the validity and reliability of the findings.

4. Fuzzy-hybrid TOPSIS

The FHT method offers several advantages, being simple and easy to use while providing a comprehensive ranking of alternatives by considering both positive and negative aspects. This makes it

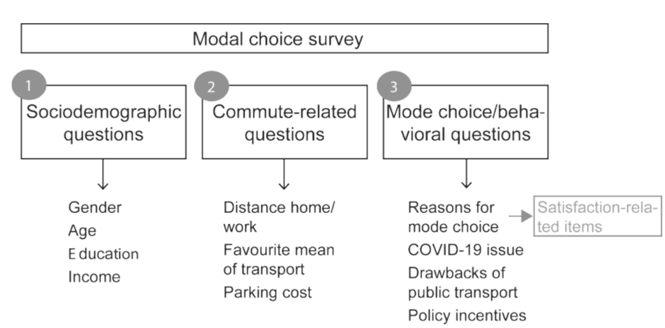

Fig. 2. Overview of the structure of the questionnaire.

Table 1
Survey sample.

Item	Group	n	%	Item	Group	n	%
FUA	Rimini (IT)	300	17.3 %	Gender	Male	750	43.20 %
	Koper (SI)	96	5.5 %		Female	975	56.16 %
	Velenje (SI)	303	17.4 %	Travel distance (km/day)	0–1 km	191	11.00 %
	Hranice (CZ)	151	8.7 %		1–5 km	546	31.45 %
	Zadar (HR)	247	14.2 %		5–15 km	424	24.42 %
	Weiz (AT)	300	17.3 %		over 15 km	527	30.36 %
	Szolnok (HU)	339	19.6 %	Travel time (min/day)	0–10 min	601	34.62 %
Age	15–29	328	18.9 %		10–20 min	524	30.18 %
	30–45	778	44.9 %		20–30 min	259	14.92 %
	46–60	552	31.8 %		30–60 min	194	11.18 %
	over60	75	4.4 %		over 60 min	59	3.40 %
Education	Primary school	60	3.5 %	Modal choice	Bike	55	3.17 %
	Secondary school	714	41.2 %		Walk	182	10.48 %
	Bachelor	335	19.4 %		Car	282	16.24 %
	Master	546	31.6 %		Motorbike	1064	61.29 %
	PhD	74	4.3 %		Bus	26	1.50 %
Occupation	PA employee	636	36.8 %		Train	86	4.95 %
	Private sector employee	691	39.8 %		Scooter	41	2.36 %
	Self-employed	185	10.8 %	Travel cost (€/month)	<50€	623	35.89 %
	Other	160	9.3 %		50-100€	405	23.33 %
	Unemployed	57	3.3 %		100-250€	202	11.64 %
Income (€/month)	under 1000€	623	35.89 %		250-500€	21	1.21 %
	1000-1500€	405	23.33 %		>500€	3	0.17 %
	1500-2000€	202	11.64 %				
	2000-2500€	21	1.21 %				
	over 2500€	3	0.17 %				

Table 2
Satisfaction-related items.

Item	Description	Likert Scale
C1	There is no other alternative	1: less important; 4: more important
C2	It is the cheapest	1: less important; 4: more important
C3	It is the fastest	1: less important; 4: more important
C4	It is the safest	1: less important; 4: more important

particularly suitable for situations where criteria conflict, such as when policymakers must choose between electric buses (low emissions but high cost) and less-green option buses (higher emissions but lower cost) for public transportation (Buran & Erçek, 2023). It is also a flexible method that can handle both quantitative and qualitative criteria (Byun and Lee, 2005). Thus, FHT is particularly useful when dealing with uncertain or imprecise information, as different respondents may have different thresholds for what they consider a "4″ versus a ″5″ on a scale, leading to vagueness and uncertainty in the raw data (Salih et al., 2019). By preserving the integrity of the original dataset, FHT allows for a richer analysis that accounts for the nuances and complexities within the dataset, avoiding the potential oversimplification that can occur with dimensionality reduction methods (Indelicato & Martín, 2023; Indelicato et al., 2024).

In this study, commuter satisfaction is measured through a hybrid approach: the indicator of satisfaction is not calculated directly on information extrapolated from the questionnaire. Rather, it is measured on raw data (extracted from the responses of the questionnaire) converted into fuzzy information, to deal with the vagueness and uncertainty of the answers provided by the respondents (Martín and Indelicato, 2023). The process is performed in a Python environment. The approach unfolds in two stages. Firstly, fuzzy logic to transform vague information into real values (Section 4.1), and then, we use the TOPSIS approach to obtain the synthetic indicator that measures the level of satisfaction (Section 4.2).

4.1. Fuzzy logic

Fuzzy logic is a mathematical approach to reasoning based on degrees of membership rather than binary values (Mamdani and Assilian, 1999). It allows for the representation of uncertain, ambiguous, or incomplete information in a way that is more reflective of how humans reason (Zadeh, 1965). One important aspect of fuzzy logic is the use of fuzzy sets, which are sets that allow for partial membership. Fuzzy sets are particularly useful in situations where it is difficult or impossible to determine whether an object or value belongs to a specific set or not (Carlsson and Fullér, 2001). In this paper, one of the numerous fuzzy sets, known as triangular fuzzy numbers (TFN), is taken into consideration.

A TFN is a fuzzy set defined on a real line with a triangular shape. It is characterized by three parameters: a, b, and c. These parameters define the lower (α_1), middle (α_2), and upper (α_3) bounds of the triangular shape, respectively (Ali et al., 2016). The degree of membership of a value x in a TFN (α_1, α_2, α_3) is given by Formula 1:

$$\mu_a(x) = \begin{cases} \dfrac{x - a_1}{a_2 - a_1} \\ \dfrac{a_3 - x}{a_2 - a_3} \\ 0 \end{cases} \tag{1}$$

where $\mu_a(x)$ is the degree of membership of $\mu_a(x)$ in the fuzzy set, and a_1, a_2, and a_3 are the parameters of the TFN. TFNs have many applications in various fields, including engineering (Gerami Seresht and Fayek, 2018), social sciences (Indelicato and Martín, 2022), and decision-making (Lubiano et al, 2017), and are a powerful tool in the field of fuzzy logic. They allow for the representation of uncertain or ambiguous information in a way that is more reflective of how humans reason.

Furthermore, the TFNs used in our analysis, as depicted in Table 3, are derived from the conversion of semantic scale into TFN of Martín et al. (2020), ensuring consistency and comparability in methodology. This approach allows for the proper handling of information ambiguity

Table 3
Triangular Fuzzy Numbers (TFNs).

Likert Scale	TFNs
Less Important	(0, 0, 20)
2	(16, 33, 60)
3	(49, 66, 83)
More important	(80, 100, 100)

inherent in survey responses by leveraging the overlapping nature of consecutive TFNs. By focusing the highest degree of truth strength at the center of each TFN triplet, our methodology effectively captures and represents the nuanced variations in respondents' perceptions and judgments regarding semantic points on the Likert scale (Indelicato et al., 2024). Thus, TFNs serve as a robust framework for translating qualitative data into quantitative fuzzy representations, facilitating a more nuanced and comprehensive analysis of complex decision-making scenarios.

To obtain aggregate TFNs for each group of analysis, Fuzzy Set Logic will be used. Thus, the average fuzzy number, for each group is given as follows (Formula 2):

$$\widetilde{A} = (a_1, a_2, a_3) = \left(\frac{1}{n}\right) \otimes \left(\widetilde{A}_1 \oplus \widetilde{A}_2 \oplus \dots \oplus \widetilde{A}_3\right) = \left(\frac{\sum_{i=1}^{n} a_1^{(i)}}{n}, \frac{\sum_{i=1}^{n} a_2^{(i)}}{n}, \frac{\sum_{i=1}^{n} a_3^{(i)}}{n}\right) \quad (2)$$

where $\otimes$ stands for the multiplication of a scalar and a TFN, and $\oplus$ is the internal addition of TFNs (Buckley,1985). Thus, a TFN matrix of each analyzed group is obtained. These matrixes contain lots of information that is difficult to interpret. Thus, following Kumar (2017), the matrix is defuzzified into a matrix of real numbers, i.e., that contains crisp numbers or clarified information. Crisp values, in the context of fuzzy logic and defuzzification, refer to the process of converting fuzzy numbers (TFNs) into precise, non-fuzzy numerical values. This conversion is essential for making the results of fuzzy logic computations interpretable and actionable in real-world applications. Thus, crisp values are the weighted average of the 3-tuple given by Formula 3:

$$C_{\tilde{A}} = \frac{(a_{i1} + 2a_{i2} + a_{i3})}{4} \quad (3)$$

4.2. TOPSIS

Multi-Criteria Decision Making (MCDM) methods evaluate alternatives based on multiple criteria or attributes. Decision-makers are required to rank alternatives based on these criteria, and the decision-making process can become complex when the criteria conflict with each other or when the alternatives to evaluate are numerous (Chen et al., 2011).

TOPSIS is a well-known MCDM method developed by Hwang and Yoon (1981). It is a decision-making technique that considers both the positive and negative aspects of each alternative and ranks them based on their similarity to the ideal solution. In this study, we employ TOPSIS for multicriteria assessment, focusing on evaluating alternatives (Age, Education, Occupation, Income (€/month), Gender, Travel time, Travel distance, Modal choice, and Travel cost) across criteria (There is no other alternative; It is the cheapest; It's the fastest; It is the safest). Following Cantillo et al. (2020), the TOPSIS method consists of three consecutive steps, starting with the determination of the ideal solutions: the positive ideal solution (PIS) is the alternative that has the highest crisp value for each criterion, while the negative ideal solution (NIS) is the alternative that has the lowest score for each criterion. Mathematically (Formulas 4 and 5):

$$PIS_j = \left\{ \left(maxC_{\tilde{A}}\right), j = 1, 2, 3, 4 \right\}, i = 1, 2, \cdots, 38 \quad (4)$$

$$PIS_j = \left\{ \left(minC_{\tilde{A}}\right), j = 1, 2, 3, 4 \right\}, i = 1, 2, \cdots, 38 \quad (5)$$

where $i = 1to38$ (groups), $j = 1to4$ (criteria). Both i and j are crisp values.

Then (Step 2), the Euclidean distances between each alternative and the positive and negative ideal solutions can be determined. The distance measures can be calculated as follows (Formulas 6 and 7):

$$S_i^+ = \sqrt{\sum_{j=1}^{J} \left(C_{\tilde{A}} - PIS_j\right)^2} \quad (6)$$

$$S_i^- = \sqrt{\sum_{j=1}^{J} \left(C_{\tilde{A}} - NIS_j\right)^2} \quad (7)$$

Finally (Step 3), the indicator that measures the travelers' satisfaction level is obtained by measuring their similarity to the ideal solutions, through Formula 8:

$$Ind_i = \frac{S_i^-}{S_i^+ + S_i^-} \quad (8)$$

The final indicator ranges between 0 and 1. A higher value indicates greater satisfaction within the reference group (Age, Education, Occupation, Income (€/month), Gender, Travel time, Travel distance, Modal choice, and Travel cost).

5. Results

Table 4 presents the TFN and defuzzified values (crisp values) that represent the entire sample analyzed in the study, by using Formulas 1–3. The overlapping TFN values are expected, as they reflect the fuzzy set theory's ability to extract information from uncertainties originating from semantic scales. However, TFNs may be difficult to interpret, causing tension and stress for readers not familiar with fuzzy set theory. Hence, it is crucial to use defuzzified values to synthesize information. From the crisp values, it is evident that commuters tend to choose the fastest mode of transportation.

After obtaining the defuzzified information matrix, an indicator is calculated to measure the satisfaction of the travelers. To evaluate the satisfaction of travelers, we use TOPSIS, which involves identifying the positive ideal solution (PIS) and negative ideal solution (NIS) scenarios for various commuter groups (Section 4). The PIS represents the scenario where each criterion (satisfaction-related items C1-C4) is at its most favorable level. In other words, it corresponds to the alternative that scores the ideal or best possible values for each criterion. Conversely, The NIS represents the alternative where each criterion is at its least favorable level. By comparing the different groups against these ideal solutions, we can assess how well each group's commuting needs are met.

Following similar studies (di Nardo & Simone, 2019; Kumar, 2017; Martín & Indelicato, 2023; Mohsin et al., 2019), the first step in TOPSIS is to compute these ideal solutions. Table 5 illustrates the crisp values corresponding to the Positive Ideal Solution (PIS) and Negative Ideal Solution (NIS) for all samples analyzed in this study, as determined using Formulas 4 and 5. The presence of alternative transportation options for commuting to work or school is deemed unimportant by individuals who walk, while those who have a commuting cost between 100–250 € perceive the existence of valid alternatives as crucial. Car commuters consider travel costs important, but those who live in Koper do not. Additionally, the speed at which one reaches their destination is a crucial factor for the satisfaction of commuters by bus, but not for those using the train. Moreover, residents of Szolnok consider safety as an important attribute, while those who have a monthly trip cost higher

Table 4
TFNs and crisp values on the total sample.

Item	TFNs	Crisp values
C1	(45.87, 60.29, 71.28)	59.78
C2	(35.57, 48.78, 64.75)	49.47
C3	(65.44, 83.13, 85.53)	80.06
C4	(58.98, 75.38, 82.67)	73.10

C1: There is no other alternative; C2: It is the cheapest; C3: It's the fastest; C4: It is the safest.
TFNs: Triangular Fuzzy Numbers.

Table 5
PIS and NIS.

Item	Group	PIS	Group	NIS
C1	100-250€	76.2	Walk	33.6
C2	Car	70.5	Koper	39.4
C3	Bus	87.9	Train	45.8
C4	Szolnok	85.3	Cost > 500€	15.2

C1: There is no other alternative; C2: It is the cheapest; C3: It's the fastest; C4: It is the safest.
PIS: positive ideal solution; NIS: negative ideal solution.

than €500 do not. The former finding might be explained by the high level of concern and conflict generated by the COVID-19 pandemic in Hungary, in turn leading to scarce confidence in the behavior of local authorities (Polyák Gábor, 2020). Commuters spending more than 500 €/month for travel, instead, might have expressed no concerns about contagion because they are, in all cases in our survey, individual drivers.

Once the ideal solutions and respective Euclidean distances have been calculated (Formulas 4–7), the TOPSIS indicator is calculated (Formula 8). The results of the analysis of each socioeconomic variable in this study are presented in Table 6, which first presents the TOPSIS indicator by FUA of the respondents and then delves into their age and gender, education, and type of employment. The second column Table 6 is mostly dedicated to travel-related variables, including distance and time, modal choice, and trip cost.

Overall, the results of the TOPSIS analysis indicate that most FUAs score satisfaction levels above 0.5, which can be considered a reasonable threshold. However, Hranice (Czech Republic) falls short of this threshold, with a satisfaction score of 0.47. Interestingly, respondents from Szolnok (Hungary) report the highest satisfaction with their commute. This could be attributed to the city's efforts to improve infrastructure and encourage the use of sustainable transport options. More in-depth considerations are reported in the discussion (Section 6), together with a broader overview of the role of socioeconomic and travel-related determinants.

Table 6
TOPSIS results measuring commuter satisfaction according to several variables.

Variable	Group	TOPSIS	Variable	Group	TOPSIS
FUA	Szolnok	0.84	Gender	Female	0.72
	Velenje	0.72		Male	0.69
	Rimini	0.72	Travel distance (km/day)	>15 km	0.81
	Koper	0.60		5–15 km	0.70
	Weiz	0.59		1–5 km	0.58
	Zadar	0.57		0–1 km	0.47
	Hranice	0.47	Travel time (min/day)	20–30 min	0.78
Age	46–60	0.73		30–60 min	0.77
	30–45	0.72		10–20 min	0.75
	>60	0.65		0–10 min	0.62
	15–29	0.62		>60 min	0.46
Education	Bachelor	0.79	Modal choice	Motorbike	0.72
	Primary school	0.73		Bus	0.68
	Secondary school	0.71		Car	0.65
	PhD	0.66		Walk	0.49
	Master's degree	0.65		Bike	0.48
Occupation	Self-employed	0.75		Scooter	0.40
	Private sector employee	0.72		Train	0.38
	PA employee	0.69	Travel cost (€/month)	100-250€	0.80
	Other	0.57		50-100€	0.79
	Unemployed	0.36		250-500€	0.71
Income	1000-1500€	0.78		<50€	0.63
	1500-2000€	0.73		>500€	0.39
	>2500€	0.68			
	2000-2500€	0.67			
	<1000€	0.56			

6. Discussion

The results show that most of the cities analyzed exceed the threshold of reasonable satisfaction (0.5), except for Hranice in the Czech Republic, indicating the need for improvements in local transport infrastructure and policies. These results reflect the importance of effectively providing conditions for commuters to benefit from multiple alternatives, reducing the otherwise hardly avoidable decision to rely on private motorized transport, as emphasized by Rotaris and Danielis (2015). Intuitively, and in line with previous literature (Wang et al., 2024), respondents express higher satisfaction when using the fastest mode, suggesting that quick arrivals contribute to overall satisfaction. However, it is crucial to recognize that factors such as cost, comfort, and convenience also influence satisfaction, as noted by Esmailpour et al. (2022). Thus, while speed is important, it is not the sole determinant of satisfaction. The study identifies several factors that influence commuter satisfaction, including age, education, income, travel distance, and time.

Age is found to be a significant factor in determining satisfaction, with commuters aged 30–45 and 46–60 reporting higher satisfaction than younger individuals, possibly due to the benefits of maintaining established habits (Plowden and Parkin, 2023) or the greater ability to choose their mode of transportation compared to younger people who may not have a driver's license or the means to purchase a car or motorcycle.

Education level has an interesting effect on commuter satisfaction. Travelers with a bachelor's degree are the most satisfied (0.79). On the contrary, highly educated people (postgraduates) are the least satisfied (0.65). These results are intriguing, but not easy to interpret. We suggest that the lower satisfaction of highly educated individuals may reflect a state of stress or frustration about the impact of the transport sector and, more specifically, their choices, in contexts where people often perceive the choice of alternatives to driving as unsuitable for their everyday needs (Meena et al., 2023). Indeed, according to the questionnaire, 63 % of doctorate holders drive to work. An alternative but complementary explanation is offered by Choi et al. (2021). They claim that Ph.D. holders occupy employment positions that intrinsically add stress and dissatisfaction to commuting because they feel or have more responsibility and thus are less flexible in their travel.

Satisfaction indexes linked to the variable "income" could support this conclusion: those earning more than 2000 €/month are not the most satisfied with their commute (0.67–0.68), reflecting stress and dissatisfaction with their choice of mode, possibly due to their multiple needs and contingencies and their awareness of the impact. On the contrary, those with an income between 1000 and 1500 €/month score 0.78, and those with an income up to 2000 € score 0.73. The least affluent commuters (income below 1000 €/month) and the unemployed are the least satisfied (0.56 and 0.36 respectively). Free ticket policies and financial incentives for choosing PT are important to encourage more people to use sustainable modes (Baptista and Marlier, 2020). However, they are only effective if the target users are in the social position to benefit from these incentives. As discussed, less affluent workers and the unemployed have limited housing and mobility choices and are often forced to live in suburban locations. Lack of access to transportation leads to difficulties in accessing employment and social opportunities, creating an equity issue. This problem is exacerbated by the cost of PT, which acts as a barrier in the absence of appropriate policies. (Bruzzone et al., 2023a, 2023b; Busch-Geertsema et al., 2021; Cavallaro et al., 2023). A further focus on disadvantaged groups (low-income and unemployed individuals) suggests that policies aimed at providing everyone with reliable and affordable alternatives to walking, a generally obligatory choice even in unsafe contexts and yet a mode that limits accessibility to distant opportunities, are needed to improve their satisfaction. Extending this perspective, the dissatisfaction of low-income commuters and the unemployed can be seen as a concurrent cause of their disadvantaged social status, rather than a consequence. In addition to structural solutions, education and awareness-raising initiatives can be effective in increasing satisfaction with sustainable transport among different age and education groups, changing perceptions of active mobility and collective transport options, and promoting social inclusion (Lättman et al., 2016).

Men and women are almost equally satisfied with their commute (0.69 and 0.72, respectively), suggesting that the gender issue, which elsewhere is a crucial factor in commuting behavior, may not be a strong argument in this context. Instead, we gain interesting insights from the results of the TOPSIS satisfaction indicator on travel time: those who commute for 20–30 min are the most satisfied (0.78), possibly reflecting the low exposure to traffic congestion, which can be a significant source of frustration for many commuters (Memon et al., 2020). A similar level of satisfaction is achieved by those who travel up to 1 h (0.77). People with longer commutes are dissatisfied (0.46), which is in line with previous literature (Ashik et al., 2024b) and seems self-intuitive, but even those who commute for 0 to 10 min only score 0.62. This could be due to a lower perception of satisfaction associated with an overall short, walkable, almost effortless trip, reducing the dissonance between expected and actual commute times, as suggested by Clark et al. (2020) and Ye et al. (2020). While walking is a satisfactory solution for short commutes, it can become a frustrating option when it is a forced choice due to a lack of alternatives or economic/social opportunities, as highlighted above. Overall, walking as a modal choice scored only a satisfaction index of 0.49, below the satisfactory threshold. Cycling scored 0.48, contributing to a demoralizing picture for active mobility. Meanwhile, the satisfaction index for short trips (up to 1 km) is 0.46, a figure that rises progressively with trip length, reaching 0.81 for trips over 15 km, likely to be made by car or motorbike. These results support the vision of the use of active modes as a mandatory solution rather than a free choice. Contrary to the active modes, and partly in contrast to previous literature (Lunke, 2020), the bus service is satisfactory, with a score of 0.68. Interestingly, however, the performance of PT is not homogeneous: in contrast to bus users, train users are the least satisfied of all commuters (0.38). This may be because trains in Central Europe often do not offer satisfactory standards in terms of speed, comfort, frequency and reliability, the lack of integrated ticketing, and the absence of structured suburban services in the FUAs analyzed, apart from Weiz (Smart Commuting, 2020). Car commuters have a satisfaction score of 0.65, which reflects well the appreciation of the speed and reliability of the option, but also the intrinsic stress and, for some social groups, the stigma associated with the unsustainable -but sometimes unavoidable-choice.

These findings provide valuable insights for policymakers and planners to improve transportation infrastructure and policies, particularly in reducing congestion, promoting active modes, and minimizing travel time uncertainty of PT. Efforts to reduce traffic congestion and promote cycling and walking, such as implementing bike lanes and pedestrian walkways, are consistent with Higgins et al. (2018) and improve the commuter experience. Furthermore, the provision of high-quality PT is consistent with these goals (Bruzzone et al., 2023b). The FUAs that focus more on the centrality of PT and active modes show higher commuter satisfaction, regardless of the modal split. This is the case in Rimini, which invested significantly in protected bike lanes, the historic trolleybus network, and a new interurban right-of-way e-busway known as MetroMare (Comune di Rimini, 2024); Velenje, offering free local PT throughout the city and its valley and boasting a car-free city center (Mestna občina Velenje, 2024); and Szolnok, having invested heavily in the reinforcement of the PT and active transport supply under the Hungary Transport Plan 2015–2025, as well as in the digitalization of mobility (Ilie, 2024; Smart Commuting, 2020). These conclusions indicate that individual aims to enhance one's satisfaction and social objectives, such as favoring sustainable choices and decreasing the modal split of private cars, can complement each other. A combination of transport planning actions, normative innovation, economic instruments, and technological advancements can effectively promote commuting sustainability and encourage the adoption of sustainable modes. The empirical findings of this study also emphasize the importance of policy actions and infrastructure measures in achieving the EC's Sustainable and Smart Mobility Strategy goals (EC, 2020), ensuring the sustainability and well-being of future societies, as also noted by Ferretto et al. (2021).

7. Conclusions

Commuting is a relevant challenge for transportation experts and policymakers, as it generates large environmental and societal impacts, stresses urban environments and infrastructures, and profoundly affects people's well-being and life opportunities. Using a hybrid fuzzy TOPSIS approach, this study investigates the satisfaction of commuters in seven Central European cities concerning their choice of transport mode to get to work or school, their socio-economic conditions, and the geographical and mobility-related characteristics of their residential and work locations.

Overall, the empirical results provide valuable insights into the factors that influence commuters' satisfaction with their chosen mode of transport and can guide policymakers and planners in making informed decisions about transport infrastructure and policies. The fuzzy TOPSIS approach used in this study allows for the inclusion of uncertainty and imprecision in the analysis, which is a significant advantage and strengthens the relevance of the results. As a policy outcome, the reduction of travel time variability through more reliable PT and better active mobility options is shown to be an efficient strategy to increase commuter satisfaction while meeting overarching environmental and societal goals set for the transport sector. Throughout the study areas, the results also highlight the need for education and promotion of active and sustainable modes of transport to socially promote these choices and to support the emergence and recognition of their potential to reduce the stress associated with commuting.

This study provides valuable transnational quantitative and policy insights into commuters' satisfaction with their chosen mode of transportation and the factors that influence their satisfaction. However, there are some limitations to this study that could be addressed in further research. One limitation of this study is that it focuses only on seven municipalities in Central Europe that previously participated in the EU-funded Smart-Commuting project. While it is interesting to use a sample that includes several European countries, further research could expand the geographical scope of the study to include more cases, which would allow for a more comprehensive understanding of commuter satisfaction across the region. In addition, the study only examines the influence of a limited number of factors on commuter satisfaction, including age, education, occupation, gender, travel distance, travel time, commuting costs, and income. Further research could explore the influence of other factors, such as the safety and comfort of transportation modes, on commuter satisfaction. Finally, the administration of the questionnaire through online channels, social media, and interviews leaves room for improvement. Unfortunately, the global restrictions that accompanied the post-pandemic phase limited the exploration of alternative methods. However, in recognition of this limitation, we do not emphasize the generalizability of the study's findings to other contexts. Instead, we use these specific contexts to enhance our understanding of the strategic implications of commuting policies, their effectiveness within the broader framework of European transport policy, and their potential influence on the mobility patterns of European commuters.

CRediT authorship contribution statement

Alessandro Indelicato: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Francesco**

Bruzzone: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Stefania Tonin:** Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Silvio Nocera:** Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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