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Innovations in daily commuting: what types of solutions are competitive? European case study

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Abstract. Innovations drive dynamic changes in daily commuting, especially in functional urban areas (FUAs), where transport systems are developed. Innovative solutions are being tested in FUAs and they not only pose an alternative to conventional transport systems but can also revolutionise daily commuting in cities. The main aim was to classify the innovation drivers identified in the literature and to determine their impact on travel behaviour (TB) in FUAs with the use of an expert survey. The following research hypothesis was examined: the level of innovation utilisation in daily commuting and its impact on TB is similar in countries with similar levels of economic development. The survey results were processed to (1) create a ranking of innovations in TB in European OECD countries and (2) group countries based on similarity in prioritising innovations influencing TB, using the Ward hierarchical clustering method. As a result, innovative factors were comprehensively identified and classified into six categories.

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Contents:

1. Introduction

1.1. Research background

Cities implement transport policies and management strategies to provide their residents with access to various means of transport (Oeschger et al., 2020; Abduljabbar et al., 2021). City dwellers can choose from different options, such as shared transport, whereas the residents of suburban areas, especially areas that are strongly linked with the urban core, are often tasked with organising their own means of transport (Wolny, 2019). In core cities and the commuting zones, the key challenges for the local authorities are to reduce traffic congestion, prevent transport-related social exclusion, adapt means of transport to local needs, and introduce eco-friendly transport options. Functional urban areas (FUAs) should be testing grounds for innovative solutions that could offer an alternative to conventional transport and revolutionise daily commuting.

Research studies examining the influence of innovations on daily commuting patterns provide important information about the attitudes and expectations of commuters who represent different generations. A growing number of commuters are members of Generation Y (also known as Millennials, the WWW Generation, or the Net Generation) and Generation Z (also known as Zoomers, Post-Millennials, or the Internet Generation) who represent an approach that is oriented towards mobility and rapid response to change (Paukert et al., 2021). The skills and characteristics of these generations are a direct reflection of the technical progress that has been made since their birth (Baran & Kłos, 2014), which is why innovative solutions, including in daily commuting, will be important in their lives. For this reason, modern transport policies and plans (medium- and long-term) should account for the life philosophy of the youngest generations of commuters (and local community members), including their approach to innovation. As a result, the choices made by the youngest generations affect the popularity of different urban mobility and transport solutions, and they impact the competitiveness and profitability of both public and private transport.

Therefore, FUAs, where people are active users of urban transport systems, should be examined because important, dynamic changes in daily commuting are driven by innovations in the urban environment. FUAs are sub-regions that have been created due to the significant impact of cities on their surroundings, as well as temporary transformation processes in settlement, land use structure and population. The definition of FUAs proposed by the Organisation for Economic Cooperation and Development (OECD) was adopted for the needs of the present study. This definition relies on population density to identify urban cores and travel-to-work flows to identify the "hinterlands", whose labour market is highly integrated with the cores (OECD, 2013). The "hinterland" was defined as the "worker catchment area" of the urban labour market, outside the densely inhabited core (OECD, 2013). According to this definition, the travel-to-work analysis seemed to be an important issue for creating coherent FUAs. However, the definition changed in 2019 (Dijkstra et al., 2019; OECD, 2019), when it was emphasised that FUAs consist of urban cores (cities) and commuting zones that are composed of local administrative units where at least 15% of the workforce commutes to the city (Dijkstra et al., 2019; OECD, 2019). The main effects of innovations include changes in travel behaviour (TB), in particular in daily commuting patterns. In view of the above definition of FUAs and the observations of their dynamic growth, where the links between urban and rural zones are based on daily commuting, further research into TB is needed to improve transport systems in FUAs.

Travel behaviour is defined as a set of practices in response to the availability of transportation resources and a supportive context for enabling travel (Barajas, 2021). Considerable research has been done on TB despite the fact that this field of research gained popularity only in the 1980s (Davis et al., 2020). Research on TB generally explores daily commuting patterns in FUAs, and it considers atomised transport (individuals or groups of passengers) (Rodrigue, 2020), as well as massified public transport (Nguyen-Phuoc et al., 2018; Bartosiewicz & Pielesiak, 2019; Almlöf et al., 2020; Echaniz et al., 2022). Previous studies analysed innovative solutions in transport systems that improve daily commuting experiences and evaluated the impact of individual solutions such as vehicle sharing systems (García-Palomares et al., 2012; Kwiatkowski, 2018; Mounce & Nelson, 2019; Bieliński & Ważna, 2020; Duran-Rodas et al., 2020; Shaheen et al., 2020; Soriguera & Jiménez-Meroño, 2020; Schimohr & Scheiner, 2021), autonomous vehicles (Lenz & Fraedrich, 2016; Duarte & Ratti, 2018; Hancock et al., 2019), park-and-ride systems (Zhang et al., 2018; Cavadas & Antunes, 2019), GPS and applications for travel planning and tracking vehicles (Zhang et al., 2013; Andersson et al., 2018; Tang et al., 2019), woonerven (Vasileiadis & Nalmpantis, 2019; Ferenchak & Rowangould, 2020; Kopeć & Wojtowicz, 2021), as well as the impact of remote work and Internet shopping on daily travel in general (Loo & Wang, 2018; Campisi et al., 2022; Rafiq et al., 2022). However, a single approach to evaluating the combined impact of numerous innovations has not been proposed to date. Most studies have emphasised the importance of innovations in the local, regional or national context, but the solutions adopted in FUAs should be examined from an international perspective due to the rapid transfer of innovations between dynamically developing areas, including FUAs.

It should be emphasised that most of the studies on TB concentrate on selected age and social groups (children, students, women, seniors, families with children, etc.) and a limited set of TB (individual or public), in particular discrete TB (Davis et al., 2020). Another popular research topic is the utility of various transport modes to explain the differences in TB across countries (Buehler, 2010). However, further research is essential to determine innovative factors influence on the behaviour of various commuter groups who rely on modes of transport that are both "active" (where travellers independently choose the hour of departure, the travelled route, and co-travellers) and "passive" (organised transport, where the route, duration of travel, and departure times are fixed), as well as multimodal transport (conventional means of transport combined with modern solutions). There is also a need to identify and classify factors that affect travellers as they adapt to changing conditions.

1.2. Aim and scope of the work

The main purpose of this research was to comprehensively classify the factors that have been identified in the literature as innovation drivers and to determine their impact on TB in FUAs. The present research is innovative for three reasons: (1) the innovative factors influencing TB in FUAs were comprehensively identified and classified in 6 categories (social, economic, legal, infrastructural, technological / SMART, and environmental) - after (Dudzińska et al., 2023); (2) the prioritisation of innovative factors in European OECD countries characterized by varying levels of economic development were determined, and (3) a clustering of European OECD countries based on assigned innovation factors in transportation was conducted using the Ward method. Preliminary research - at the desk research stage involving analysis of literature and sources from a number of countries - confirmed the impact of various innovations on TB. The pilot study - in the form of interviews with experts from different countries - indicated that there is a link between a country's level of wealth, its degree of socio-economic development and the introduction of innovation (including in the area of TB). Hence the following research hypothesis was examined: the level of innovation utilization in daily commuting to work and its impact on TB is similar in countries with similar levels of economic development.

The study was conducted with a use of a survey method. The survey involved experts from European OECD countries and two OECD candidate countries. The questionnaire survey was limited to European countries which share the following similarities: a single market, free flow of goods, services, technology, and innovation (in particular in the EU and the associated countries). This multidimensional comparative analysis of expert opinions on innovative factors that affect TB will contribute valuable information about the choice of commuting modes in FUAs. Innovations play a very important role in the lives of Gen Y and Gen Z members, and their significance has to be recognised in the process of developing transport policies nowadays.

2. Materials and methods

Empirical analyses both qualitative (literature review, questionnaire survey) and quantitative (statistical analysis to rank innovative factors) were conducted to validate the research hypothesis. Statistical, geographic and analytical tools were used in the study

(Statistica PL v. 13 and QGIS 3.28.6). A list of potential innovations that affect TB in FUAs was developed based on a review of the literature. Innovative factors that have been identified in the literature in the past 30 years (ever since the first innovations, even the most incidental, have been reported) were aggregated. The following step, the identified innovative factors were classified and grouped in six categories (*social, economic, legal, infrastructural, technological/SMART and environmental*) (Dudzińska et al., 2023).

An online questionnaire was designed based on the identified factors. The questionnaire was addressed to experts from areas such as: transport, urban planning, urban development and administration in European OECD countries and OECD candidate countries. The survey results were processed to (1) create a ranking of innovations in TB in European OECD countries and (2) group countries (using the Ward hierarchical clustering method) based on similarity in prioritising those innovations influencing TB. Figure 1 presents the applied research procedure.

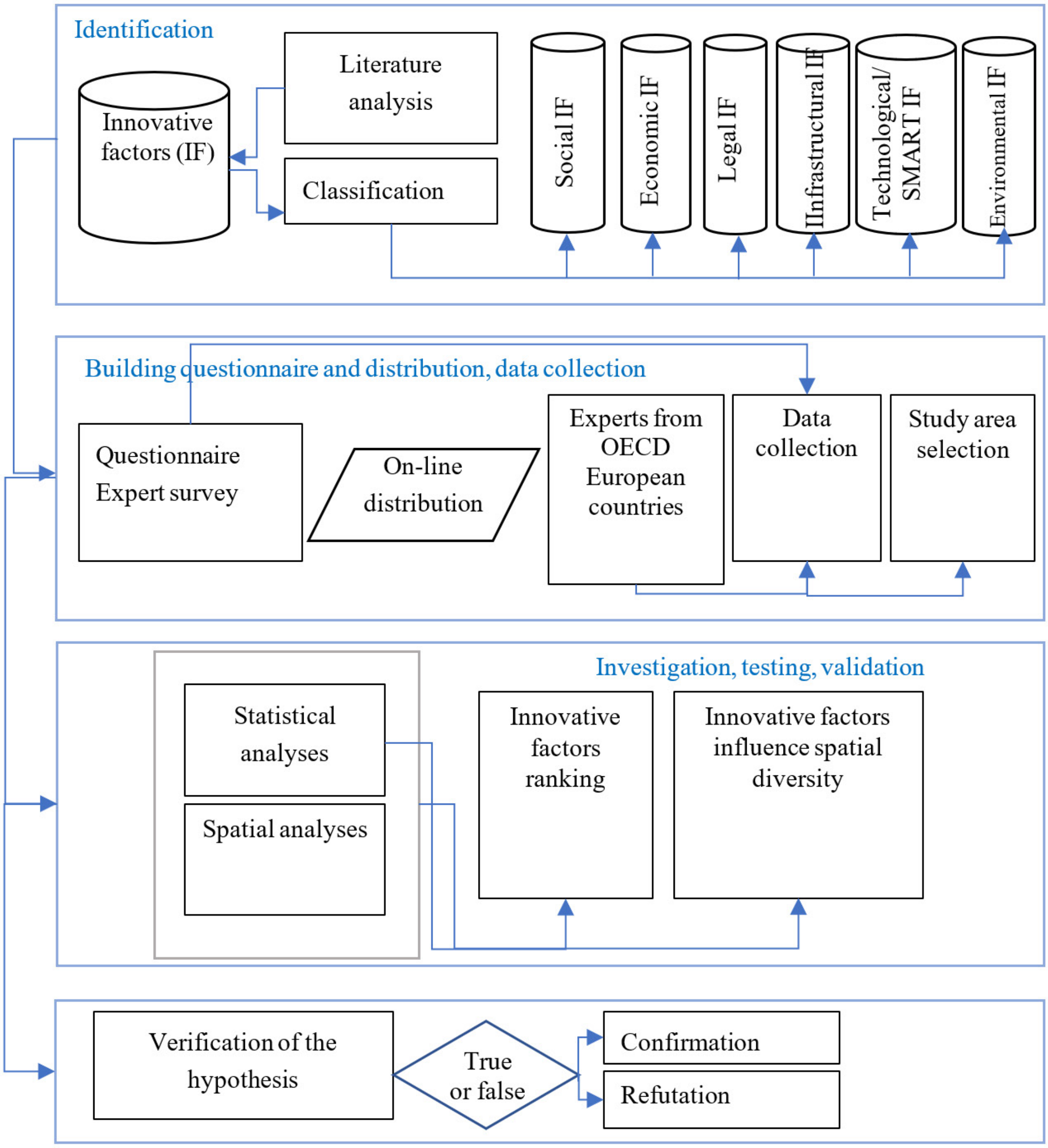


Fig. 1. Research framework
Source: authors' elaboration

2.1. Questionnaire and data processing

The survey questionnaire comprised 12 questions, a few of which were designed to collect information about the respondents (e.g., main field of interest, employment in a commercial organisation or a research/educational institution, and professional experience). The first part of the questionnaire contained single- or multiple-choice closed-ended questions. The respondents also indicated their continent and country of residence in a descriptive question. Closed-ended questions addressed innovations that influence TB. Then, the participants were asked to select the most relevant factors in six groups that influence TB.

The respondents could give a maximum of three answers to each question, which implies that the number of factors selected in each question could differ. The questions also differed in terms of numbers of potential answers, which corresponded to the number of potential innovations. In this group of questions, the participants were asked to identify such innovations that may have an impact on the entire society rather than on individuals. In the last question, experts were asked to rank six groups of factors from the most to the least relevant.

2.2. Statistical and geostatistical methods

The responses from the surveys were statistically analysed using two techniques: Weighted Sum Ranking and positional technique. In Weighted Sum Ranking, expert opinions regarding the order of selected indicators were considered. Weighted Sum Ranking is an evaluation technique that assigns different weights to individual positions occupied by features or elements in the study. Each position occupied by a feature by respondents is weighted by a specified weighting coefficient.
The formula for the sum rank *Si* for the i^{th} feature is:

$$S_i = \sum_{j=1}^{k}(w_{ij} * r_{ij}) \quad (1)$$

where:
S_i is the weighted sum rank for the i^{th} feature,
n is the number of respondents,
w_j is the weighting coefficient for the j^{th} position,
r_{ij} is the rank assigned by the respondent j to the i^{th} feature.

In determining the rank within a given group for each expert's response, the order of indications was taken into account on a scale: first position – 3 points, second position – 2 points, third position – 1 point, and features not indicated remained unranked. The results were compiled for the six groups of factors and all experts.

The positional technique was applied when it was essential to establish the order of features rather than their absolute value. The positional scale can take various forms, but it is most commonly based on arranging elements according to their relative positions. In the context of survey analysis, this scale allows for a comparison of which features respondents perceive as more important relative to others, without precisely determining the absolute difference between their values.

By applying both of these techniques, the analysis of survey data becomes more comprehensive, enabling an understanding of both the significance of individual features and their relative order in the context of the study.

The Ward method is a hierarchical clustering technique for grouping objects, with the goal of minimising variance within clusters and maximising the difference between clusters. In the first step, each object is treated as a separate cluster. Subsequently, distances between clusters are computed by merging the closest ones. After merging, a new cluster variance is calculated. This process is repeated until a single, large cluster is obtained. The Ward method uses Euclidean distance to measure the distance between objects. The formula for the Euclidean distance between two objects, a and b, in a k-dimensional space is:

$$d = \sqrt{\sum_{i=1}^{k}(a_i - b_i)^2}\ , \quad (2)$$

Where a_i and b_i are the respective i^{th} coordinates of objects a and b in the k-dimensional space.

In the following step, weights (W_{Kj}) were assigned to the six categories of innovative factors. Weights were assigned based on the answers to the last (12th) question, in which the respondents were asked to prioritise the identified categories of factors (1–6). Weights were computed based on the location and number of indications relating to a given category (K_j). The responses were ranked by multiplying the corresponding weights by the number of times a response was given:

$$W_{Kj} = {K_j}\Big/{\sum_{j=1}^{m} K_j} \quad (3)$$

The obtained values were ranked from the highest to the lowest and divided into four quartiles (irrelevant, low, medium and high) with an equal number of observations for each factor. The first (lower) quartile (Q1) is the 25th percentile, which implies that 25% of the observations are smaller than or equal to that value, and 75% of the observations are higher than or equal to that value. The third (upper) quartile (Q3) is the 75th percentile, which indicates that 75% of the data are smaller than or equal to that value, and 25% of the data are higher than or equal to that value.

2.3. Study area

The survey results were used to accomplish: (1) ranking of innovations in TB in European OECD countries, and (2) based on the similarity in prioritising innovations influencing TB, the survey results were used to group 20 European countries belonging to the OECD using the Ward hierarchical clustering method (Fig. 2).

In these countries, FUAs have been delimited and classified according to the definition (Dijkstra et al., 2019). This definition was applied to 33 OECD member countries, Colombia, and all European Union Member States. The group of the analysed countries included nine OECD founding countries that have been members of the OECD since 1961, as well as Finland which joined the OECD in 1969 (Fig. 2). Eight countries that joined the OECD in the late 20th or early 21st century after political transformations were also included in the analysis. Bulgaria and Romania were included in the study as OECD candidate countries.

The research area was divided into categories, taking into account the Gross Domestic Product (GDP) *per capita* in Purchasing Power Standards (PPS) ("Statistics – Eurostat," 2023) for the year 2022, to include countries with diverse levels of economic development. Figure 3 presents countries in three main groups by high, medium and low levels of development. These categories include countries with the highest level of development, such as Sweden, Finland, the Netherlands, Germany, Norway, Italy and Austria; countries with a low level of development, such as Latvia, Slovakia, Hungary, Greece, Turkey, Romania and Bulgaria; and the remaining countries with a medium level of development (Fig. 2).

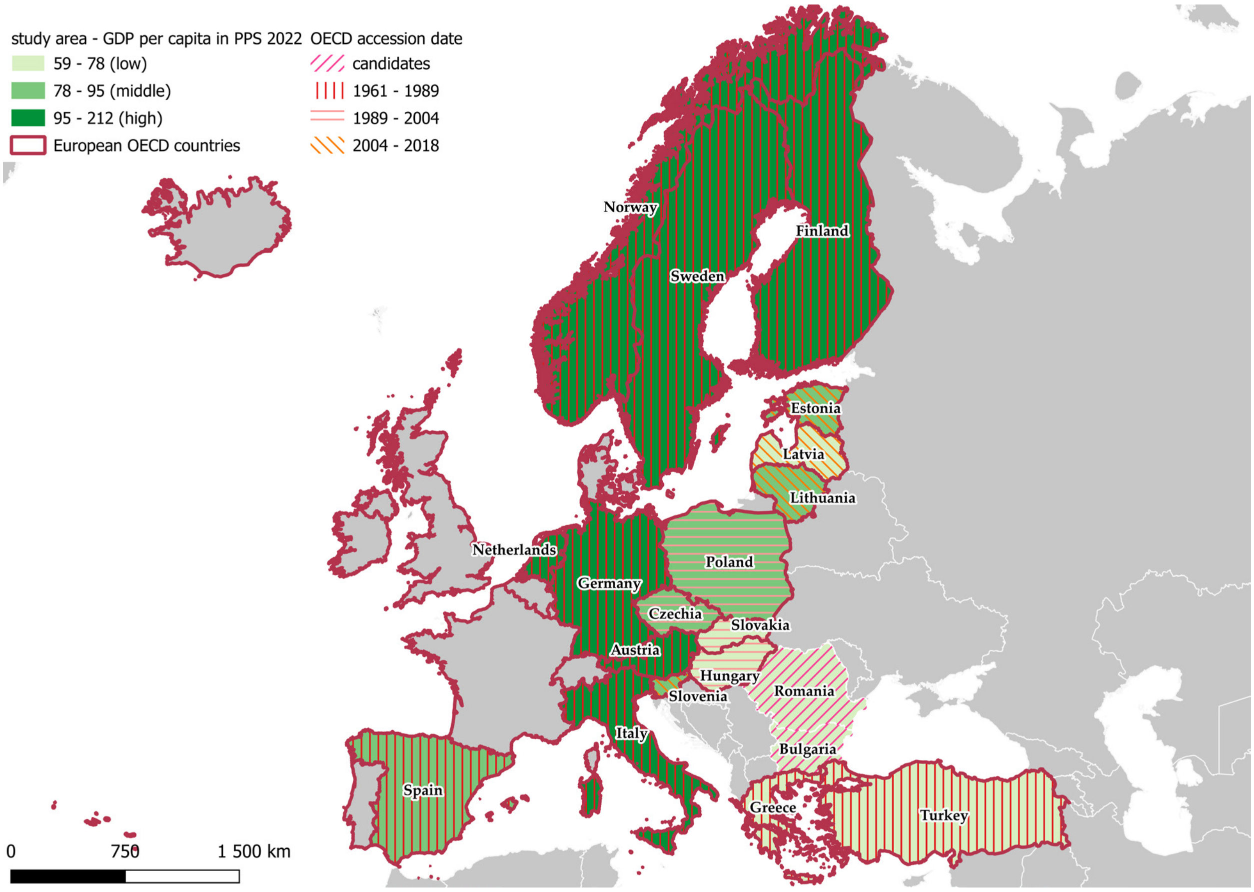


Fig. 2. Study area countries - classification according to GDP per capita in PPS ("Statistics – Eurostat," 2023) and their accession to OECD
Source: authors' elaboration

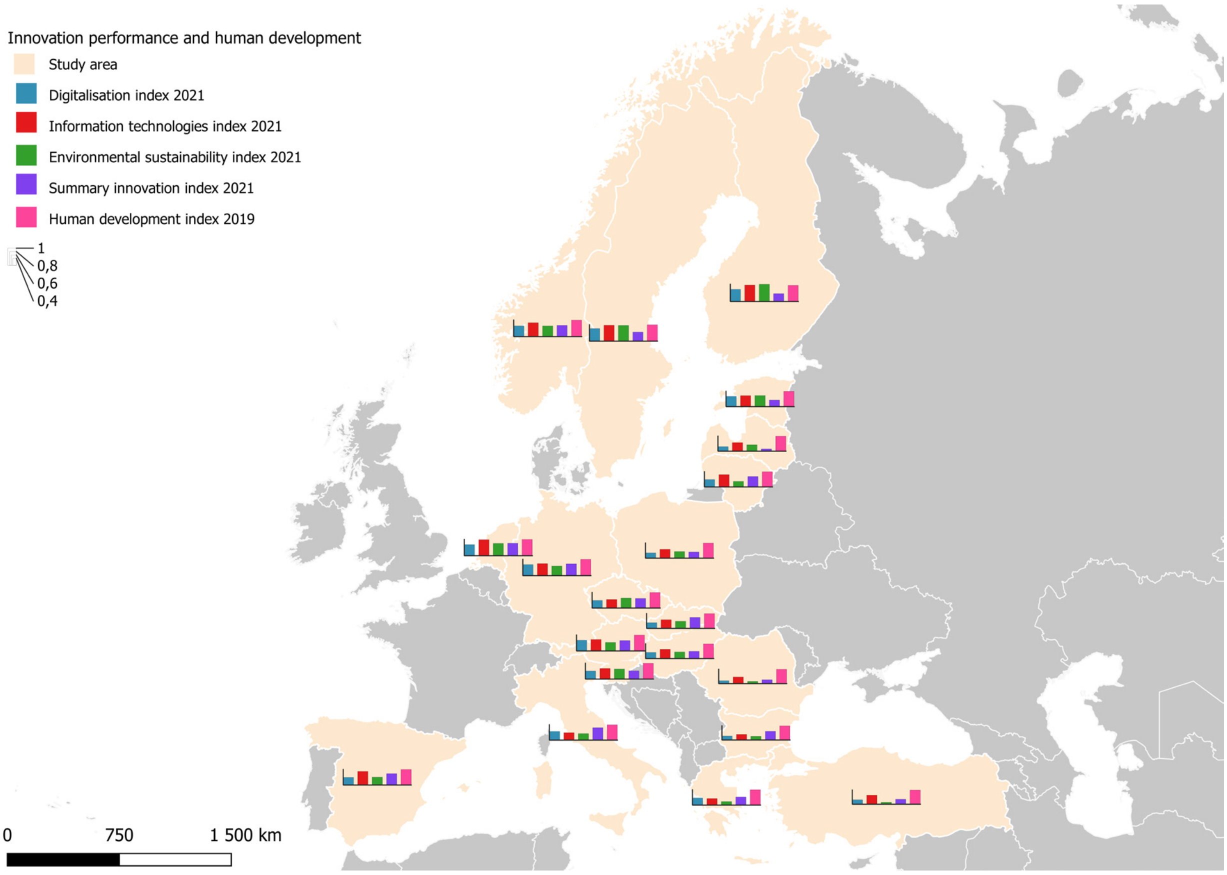


Fig. 3. Innovation performance and human development index
Source: authors' elaboration

European countries vary in terms of innovative priorities, technological advancement, availability of financial resources, and the effectiveness of public policy. For instance, Nordic countries and Germany often lead in innovation by investing in the development of new technologies, infrastructure and research programmes. In contrast, Central European countries may prioritise other aspects, such as the modernisation of transportation infrastructure or the support of entrepreneurship. These differences stem from the diversity of economies, public policies and cultural conditions in individual European countries.

The analysed countries stood out with high innovation indicators, determined based on factors such as digitalisation, the implementation of information technologies, and sustainable environmental development. Additionally, human development indicators were taken into account (Hollanders et al., 2021; United Nations, 2020). These data clearly show (Fig. 3) that innovation potential increases in parallel with the rise in GDP per capita in PPS. In 2021, the leaders in innovation included Sweden, Finland, the Netherlands, Germany, Norway and Austria. The first three countries also demonstrated the most progress in implementing innovative digital and information technologies. The level of innovation was at its lowest in Bulgaria, Romania and Turkey, correlating with the relatively lower GDP per capita in PPS values of these countries. However, all analysed countries exhibited equally high values of the Human Development Index (2019), which, combined with the dynamic economic development of "new" OECD members and an increasing level of social prosperity, should support the implementation of innovative solutions.

3. Results

3.1. Innovations influencing TB in FUAs

Research studies published in the last 40 years were reviewed with the use of Scopus, Web of Science Core Collection and Google Scholar browsers based on the keywords "TB", "passenger transport" and "transport innovations", which yielded 189 items.

Table 1. Classification of innovations influencing TB in FUAs

GROUP	INNOVATIVE FACTORS		REFERENCES	CPT*	COT*	EPT*	EOT*	APT*	AOT*
	Code	name							
1. SOCIAL	A1	Remote work	(Campisi et al., 2022; Huang et al., 2023; Loo and Wang, 2018; Rafiq et al., 2022)	X	X	X	X	X	X
	B1	Means of transport that meet the family's needs (e.g. new vehicles and safety features)	(McCarthy et al., 2017)	X	X	X	X	X	X
	C1	Improvement in health status and physical condition	(de Nazelle et al., 2011; Norwood et al., 2014; Reimers et al., 2022)					X	X
	D1	Less crowded public transport (metro, bus, tram)	(Begg, 2016; Echaniz et al., 2022; Stępniak et al., 2019; Yap and Cats, 2021)	X		X			
	E1	Positive, passenger-friendly image of public transport (additional functionalities – Wi-Fi, charging sockets, commuter trains, etc.)	(Soza-Parra et al., 2019)	X		X			
	F1	Eco-conscious attitude (public transport is chosen for environmental reasons)	(Garcia i Sierra, 2014; Nilsson and Küller, 2000)			X	X	X	X
	G1	Solutions that improve safety in public transport (security, scanners, sensors, etc.)	(Ayton et al., 2019; Crijns et al., 2017)	X		X			
	H1	Higher travel comfort	(Abdullah et al., 2020; Awad-Núñez et al., 2021; Javid et al., 2022)	X	X	X	X	X	X
	I1	Improved road aesthetics	(Blitz and Lanzendorf, 2020; Van Acker and Witlox, 2009)	X	X	X	X	X	X
2. ECONOMIC	A2	Purchase of modern means of transport	(Hoen and Koetse, 2014; Sierpiński, 2012)		X		X		X
	B2	Cheap and easily available spare parts and repair services	(Hong et al., 2020)		X		X		X
	C2	More ticket purchasing options	(Dorbritz et al., 2009; Hörcher et al., 2018; Liljamo et al., 2020)	X		X		X	
	D2	Higher service frequency (such as a bus line), changes in public transport timetables	(Sierpiński, 2012)	X		X			
	E2	Discounts / special offers for public transport passengers / ticket sharing	(Hörcher et al., 2018)	X		X		X	
	F2	Decrease in fuel/electricity prices	(Hoen and Koetse, 2014; Turrentine and Kurani, 2007)	X	X	X	X		
	G2	Expanding of transport services (new, competitive transport operators)	(Farahmand et al., 2021; Lenz and Fraedrich, 2016)	X		X		X	
3. LEGAL	A3	Acquisition of driver's license or passenger transport license	(Clark et al., 2016)	X	X	X	X		
	B3	Traffic calming in downtown areas (woonerf)	(Ferenchak and Rowangould, 2020; Topp and Pharoah, 1994)	X	X	X	X	X	X
	C3	Expansion of areas that are accessible to shared vehicles (cars, bikes, scooters etc.)	(Duran-Rodas et al., 2020; Lazarus et al., 2020; Moran et al., 2020; Schimohr and Scheiner, 2021)	X		X		X	
	D3	Speed limits	(Elliott et al., 2003)	X	X	X	X	X	X
	E3	Introduction of legislation restricting or banning the use of high-emission vehicles (e.g. diesel) in cities or their parts	(Invernizzi et al., 2011; Möhner, 2018)	X	X	X	X	X	X
	F3	Introduction or expansion of paid parking zones in the city	(Kubala and Kulpa, 2015; Meland, 1995)		X		X		
4. INF RAST	A4	Construction of new roads, road upgrades, bike paths, etc.	(Mouratidis et al., 2019; Stappers et al., 2018)	X	X	X	X	X	X

Table 1 continiued.

	B4	New traffic solutions, such as new street junctions or underground tunnels	(Thao and Ohnmacht, 2020)	X	X	X	X	X	X
	C4	New parking spaces or increased availability of parking spaces (for different types of vehicles)	(Heinen and Buehler, 2019; Mouratidis et al., 2019)	X	X	X	X	X	X
	D4	Increase in the number of public transport stops	(Thao and Ohnmacht, 2020)	X		X			
	E4	Availability of transit hubs and park-and-ride (P&R) facilities	(Cavadas and Antunes, 2019; Mouratidis et al., 2019)	X	X	X	X		
	F4	Shorter commuting time	(Jiang et al., 2017; Makino et al., 2018; Thao and Ohnmacht, 2020)	X	X	X	X	X	X
	G4	High-quality infrastructure	(Mouratidis et al., 2019)	X	X	X	X	X	X
5. TECHNOLOGICAL/ SMART	A5	Implementation of a system to improve punctuality of public transport	(Jiang et al., 2017)	X		X			
	B5	New charging stations for electric vehicles	(Guler and Yomralioglu, 2020; Guo et al., 2018; Huang and Kockelman, 2020)			X	X		
	C5	Innovative transport solutions, such as electric vehicles, kick scooters, scooters	(Bieliński and Ważna, 2020; Połom et al., 2020; Taczanowski et al., 2018)			X	X		
	D5	Travel planning applications	(Andersson et al., 2018; Zhang et al., 2013)	X	X	X	X	X	X
	E5	Applications for tracking public transport vehicles, shared vehicles and taxis (with the use of ITS and GPS tools); autonomous vehicles	(Becker et al., 2018; Sobral et al., 2019)	X		X		X	
	F5	Efficient traffic management system	(Avatefipour and Sadry, 2018)	X	X	X	X	X	X
	G5	Modern public transport fleet (shorter commuting time)	(Friman et al., 2020)	X		X			
6.ENVIRONMENTAL	A6	Vehicle solutions for environmental protection (e.g. catalytic converter)	(Hamidi and Zhao, 2020)	X	X	X	X		
	B6	Environmental awareness campaigns and programs	(Pazhuhan et al., 2022; Sierpiński et al., 2015)	X	X	X	X	X	X
	C6	Environmentally-friendly solutions in road infrastructure	(Dyrhauge, 2022; Girod et al., 2013; Turoń et al., 2020; Turoń and Sierpiński, 2018)	X	X	X	X	X	X
	D6	Civil engineering structures and solutions that improve road infrastructure safety (retention basins, reinforced embankments, flood banks, drainage ditches)	(Kumar, 2021; Kumar et al., 2021; *Transport infrastructure drainage: condition appraisal and remedial treatment*, 2014)	X	X	X	X	X	X
	E6	Early warning system on extreme weather events (effective crisis management)	(Merz et al., 2020; Potter et al., 2021)	X	X	X	X	X	X
	F6	Noise barriers	(Bohatkiewicz, 2014; Naess, 2006; van Wee, 2019)					X	X

Source: Based on a literature review.
*Abbreviations (Dudzińska et al., 2023): CPT - Combustion-powered public transport, COT - Combustion-powered own transport, EPT - Electric public transport, EOT - Electric own transport, APT - Active public transport, AOT - Active own transport

As a result, 41 factors were discovered based on a review of articles concerning the innovations that influence TB in the context of transport in FUAs (Table 1). Data were integrated based on the results of the literature analysis, and they were divided into six groups of factors (social, economic, legal, infrastructural, technological/SMART and environmental) (Dudzińska et al., 2023). Based on their impact, these factors were matched with means of transport that are sensitive to changes in each evaluated factor (Table 1). Modes of transport in FUAs were classified focusing on both the energy source (combustion-based, electric, muscle-powered/active) and ownership (private or public).

3.2. Results of the expert survey

3.2.1. Analysis of experts' population

A total of 154 experts from selected OECD countries and candidate countries including Austria, Bulgaria, Czechia, Estonia, Finland, Germany, Greece, Hungary, Italy, Latvia, Lithuania, Netherlands, Norway, Poland, Romania, Slovakia, Slovenia, Spain, Sweden and Turkey participated in the survey. Not all selected countries from European OECD countries and candidate countries had representatives in the expert survey, but the number of respondents was sufficient to meet the research aim. A minimum of five responses had to be obtained from each country to identify similarities and eliminate deviations. The survey was conducted between October 2021 and March 2022.

The majority (88%) of the participants were employed in research/educational institutions. Ten percent of respondents worked in land administration and commercial organisations, and 2% of them were both practitioners and researchers (Fig. 4). Two groups of respondents dominated the survey – those who had 10–20 years of professional experience, and persons with more than 20 years of professional experience: each group accounted for 38% of the analysed sample (Fig. 4). The minority of the respondents had less than ten years of professional experience (24%), but these participants are members of Generations Y and Z, and their opinions are highly valuable. The participating experts were employed in the following fields: transport (28%), land management and urban planning (12%), civil engineering (8%), geography (3%) and regional development (2%). However, most respondents identified as multidisciplinary researchers or practitioners because they chose or listed more than one field (60% of the sample). Around 7% of the respondents were employed in other fields (Fig. 4). Hence, the analysed sample was identified as sufficiently representative of the examined population.

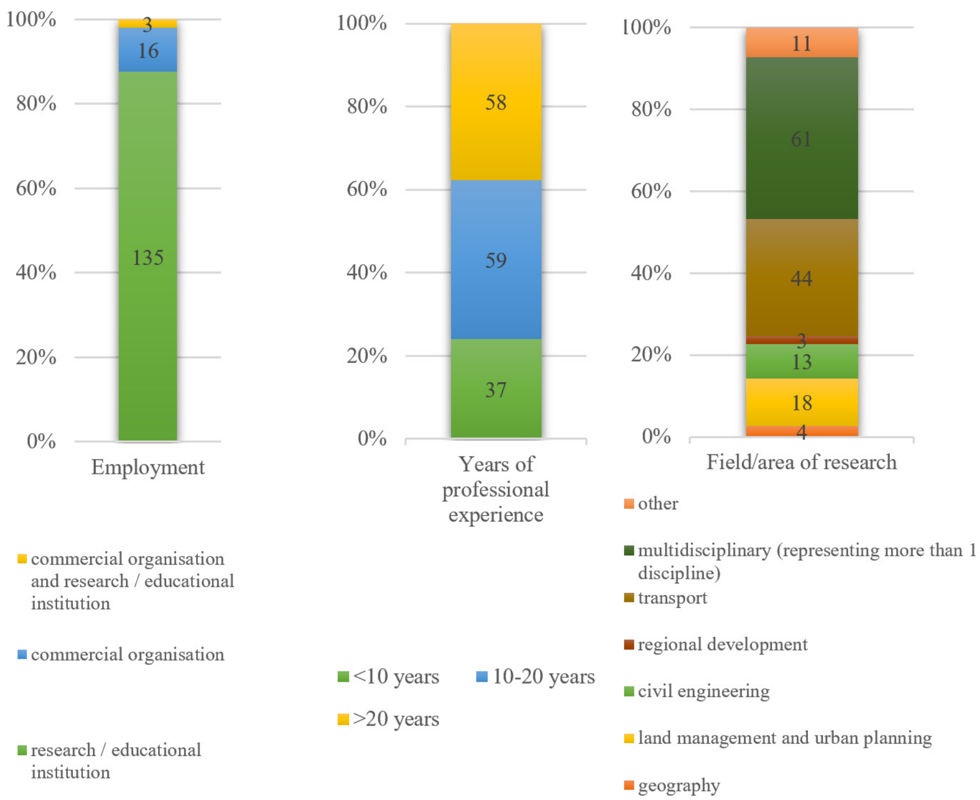


Fig. 4. Expert survey – experts' characteristics
Source: authors' elaboration

3.2.2. Innovation ranking

The ranking of innovations in TB in European OECD countries was conducted using the Weighted Sum Ranking and positional technique. In the ranking technique, each respondent's indication received a score, with the first – 3 points, the second – 2 points, and the third – 1 point. On the other hand, the positional technique took into account the number of indications of innovations. Figure 5 (a–f) presents the ranking of innovations in the analysed groups, developed based on both ranking techniques.

Innovations H1 (Higher travel comfort), D1 (Less crowded public transport – bus, tram), and A1 (Remote work) achieved the highest rank in the social factors group. Among them, innovation A1 (Remote work) received the most indications, while innovation D1 (Less crowded public transport – bus, tram) obtained the highest rank (Fig. 5a). Innovation I1 (Improved road aesthetics) turned out to be an insignificant feature, having been indicated only by three respondents.

In the economic factors group (Fig. 5b), respondents most frequently pointed to innovation E2 (Discounts/special offers for public transport passengers/ticket sharing), and the highest weight was assigned to innovation D2 (Higher service frequency (e.g., bus line), changes in public transport timetables).

In the case of legal factors (Fig. 5c), the highest rank and position were achieved by the legal feature B3 (Traffic calming in downtown areas – *woonerf*). In the group of infrastructure factors, the ranking of innovations for both ranking techniques is identical; the highest evaluations were obtained by the features E4 (Availability of transit hubs and park-and-ride facilities) and A4 (Construction of new roads, road upgrades, bike paths, etc.) (Fig. 5d).

In the next group, Technological/SMART, innovation A5 (Implementation of a system to improve punctuality of public transport) was most frequently indicated by respondents, while in the ranking technique, feature F5 (Efficient traffic management system) received the highest evaluation (Fig. 5e). The highest-rated innovation in the group of environmental factors (Fig. 7f) is innovation A6 (Vehicle solutions for environmental protection – e.g., catalytic converters).

3.2.3. The overall assessment of all proposed innovations

Based on the analysis of expert responses and ratings assigned to individual factors, the analysed factors were divided into four groups, and the extent of their impact was determined based on successive quartiles established using data collected from all questionnaires (Table 2).

Factors with scores between the third quartile and the maximum value were classified as high-impact factors. Factors with scores between the second quartile (median) and the third quartile were regarded as medium-impact factors, whereas factors with scores between the first quartile and the median were classified as low-impact factors. Factors with scores below the boundary value in the first quartile were regarded as irrelevant for TB. The ranks of factors in each group and their impact on TB are presented in Table 3.

The obtained ranking was divided into four groups based on the innovations' impact. The group of innovations with a high impact on TB included factors from the economic, social, legal, infrastructural, technological/SMART, and environmental areas.

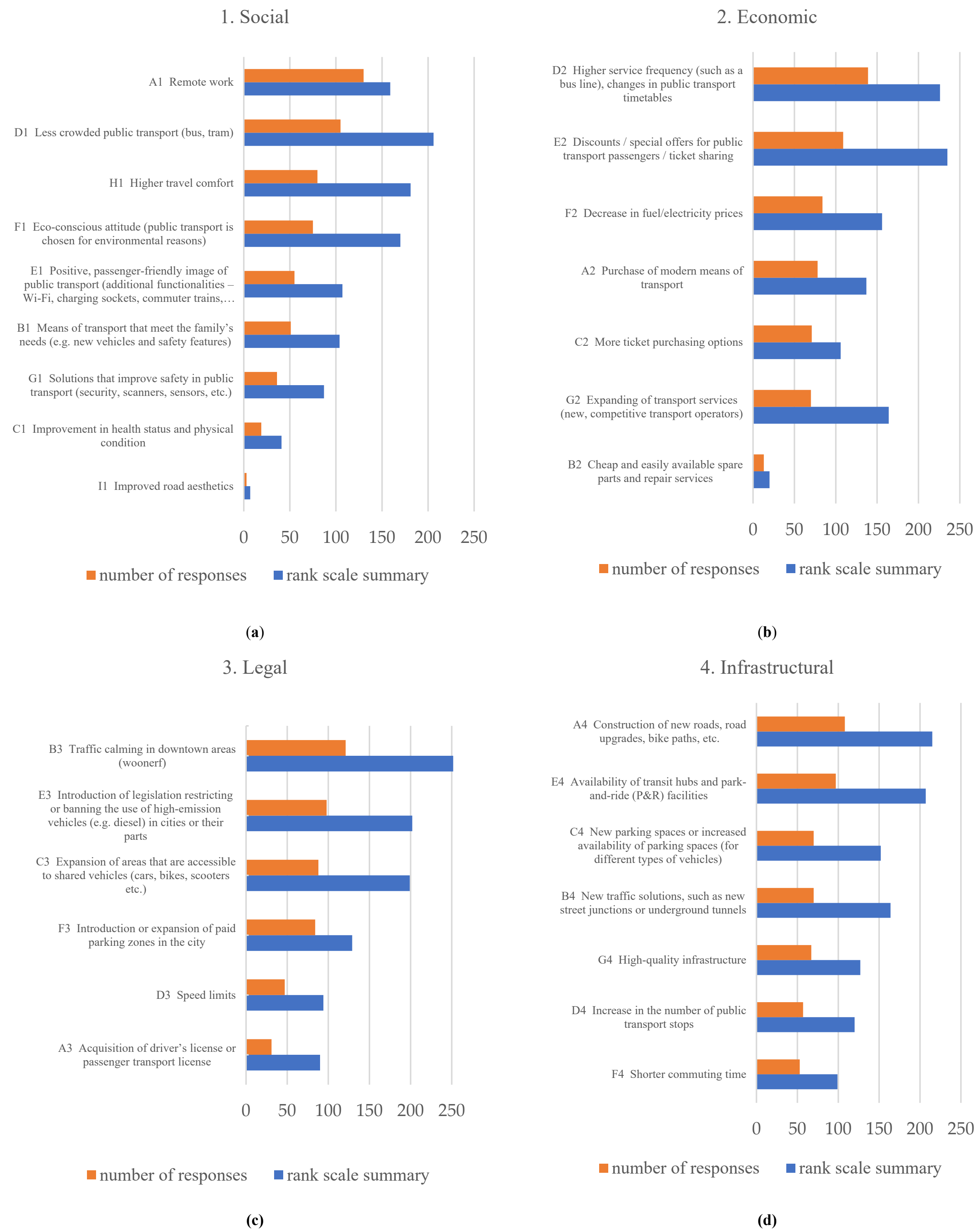
The most high-impact factors (top 3) are: Higher service frequency (D2), Remote work (A1) and Traffic calming in downtown areas (B3) (Table 3). The medium-impact group top-three factors are: Decrease in fuel/electricity prices (F2), Introduction or expansion of paid parking zones in the city (F3), Higher travel comfort (H1). Half of the factors have an impact on all transport modes, two of which only positive, and one only negative.

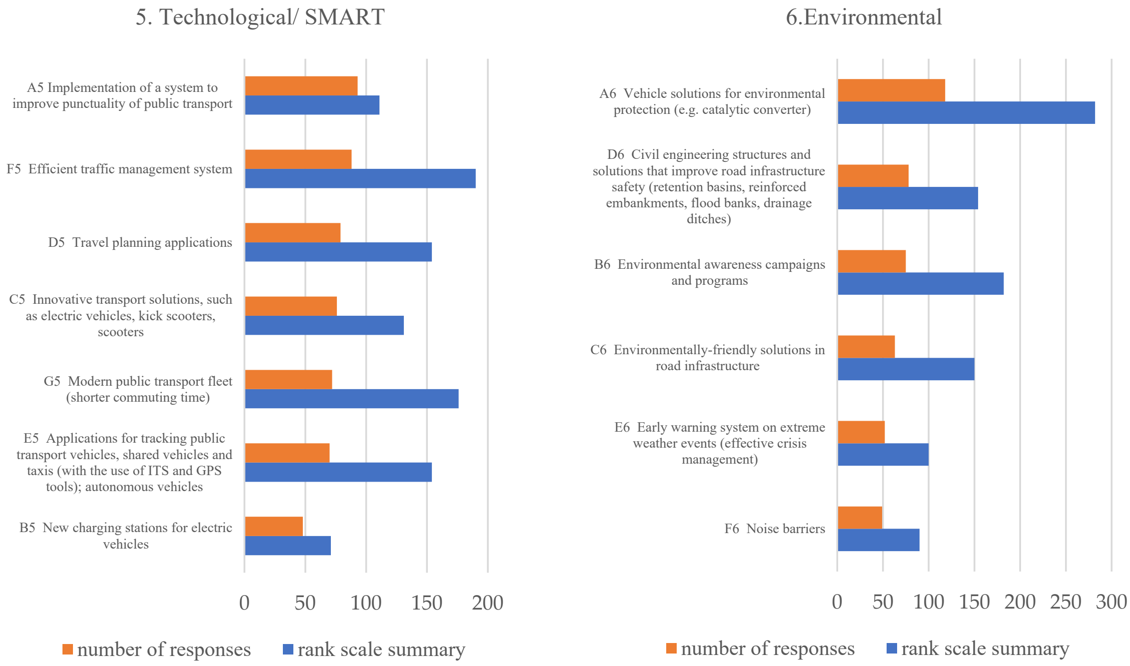
Innovations with low impact are mainly concentrated in the technological/SMART, economic, and infrastructural areas (Table 3). The highest positions in the ranking were achieved by: Modern public transport fleet (G5), More ticket purchasing options (C2), Expanding of transport services (G2). Still, most of them have a positive impact (Table 3).

The group labelled "irrelevant" includes innovations considered irrelevant in terms of their impact on travel behaviour. They mainly concern infrastructural, social, environmental, and technological/SMART factors. The factors of least significance (Table 3) turned out to be: Improvement in health status and physical condition (C1), Cheap and easily available spare parts and repair services (B2) and Improved road aesthetics (I1). In some cases, types of impacts may differ according to local regulations, which should be confirmed in case studies.

Based on the research results, all six categories of innovations were ranked. The least significant innovations were considered to be those in the Environmental category (1.45) (Table 4). On the other hand, economic (1.91) and social (1.82) factors were identified as high-impact innovations. Economic (1.91) and social (1.82) innovations were classified as the most significant (Table 4).

The distribution of expert opinions based on the recognised importance of each group of factors (12th question) is presented in Figure 6. According to the surveyed experts, economic factors exert the greatest influence on TB in FUAs. Environmental and legal factors were ranked as least important, and environmental factors were classified as least significant by 48% of the surveyed experts. The ranks assigned by experts to groups of innovative factors influencing TB are presented in Table 5.





(e) (f)

Fig. 5. Innovation ranking – comparison. Context: a) Social, b) Economic, c) Legal, d) Infrastructural, e) Technological/SMART, f), Environmental
Source: authors' elaboration

Table 2. Impact ranges based on quartiles.

Quartile number or statistic name	Upper limit of the range	Impact
max	139	high
3	88	medium
2 (median)	73.5	low
1	53.5	irrelevant

[a]In reference to number of responses
Source: authors' elaboration

3.2.4. Prioritisation of innovations influencing TB in cluster analysis

Cluster analysis was conducted to verify the research hypothesis that assumes that the level of innovation utilisation in daily commuting to work and its impact on travel behaviour are similar among countries of similar levels of economic development. Responses provided by experts from 20 countries were aggregated using the Ward method. For analysis, groups of factors classified as belonging to the category of innovations with high and medium impact on travel behaviour were selected. In total, 21 factors were chosen (4 social, 4 economic, 4 legal, 2 infrastructural, 4 technological/ SMART, 3 environmental).

Using the Statistica PL v. 13 software, a dendrogram was created, allowing the hierarchical relationships between objects to be presented based on decreasing similarity (Fig. 7). A criterion for the minimum number of objects in a group was predefined that required each created group to contain at least four objects. This assumption arises from the previously established criterion of economic wealth, where in each of the three groups of economic prosperity, at least four countries had to be included in the analysis to achieve comparability of results. The choice of the Ward method was based on its ability to minimise within-group

Table 3. Innovative factors influencing TB – the ranking

Innovative factors (code*)	Number of responses	Impact	Innovative factors	CPT*	COT*	EPT*	EOT*	APT*	AOT*
D2	139		Economic	▲	▬	▲	▬	▬	▬
A1	130		Social	▼	▼	▼	▼	▼	▼
B3	121		Legal	▼	▼	▼	▼	▲	▲
A6	118		Environmental	▲	▲	▲	▲	▬	▬
E2	109		Economic	▲	▬	▲	▬	▲	▬
A4	108		Infrastructural	▲	▲	▲	▲	▲	▲
D1	105	high	Social	▲	▬	▲	▬	▬	▬
E3	98		Legal	▼	▼	▲	▲	▲	▲
E4	97		Infrastructural	▲	▼	▲	▼	▬	▬
A5	93		Technological/ SMART	▲	▬	▲	▬	▬	▬
C3	88		Legal	▼	▬	▼	▬	▲	▬
F5	88		Technological/ SMART	▲	▲	▲	▲	▲	▲
F2	84		Economic	▼	▲	▼	▲	▬	▬
F3	84		Legal	▬	▼	▬	▲	▲	▲
H1	80		Social	▲	▲	▲	▲	▲	▲
D5	79		Technological/ SMART	▲	▲	▲	▲	▲	▲
A2	78	medium	Economic	▬	▲	▬	▲	▬	▲
D6	78		Environmental	▲	▲	▲	▲	▲	▲
C5	76		Technological/ SMART	▬	▬	▲	▲	▬	▬
F1	75		Social	▬	▬	▲	▲	▲	▲
B6	75		Environmental	▼	▼	▲	▲	▲	▲
G5	72		Technological/ SMART	▲	▬	▲	▬	▬	▬
C2	71		Economic	▲	▬	▲	▬	▲	▬
G2	70		Economic	▲	▬	▲	▬	▲	▬
C4	70		Infrastructural	▼	▲	▼	▲	▲	▲
B4	70	low	Infrastructural	▲	▲	▲	▲	▲	▲
E5	70		Technological/ SMART	▲	▬	▲	▬	▲	▬
G4	67		Infrastructural	▲	▲	▲	▲	▲	▲
C6	63		Environmental	▲	▲	▲	▲	▲	▲
D4	57		Infrastructural	▲	▬	▲	▬	▬	▬
E1	55		Social	▲	▬	▲	▬	▬	▬
F4	53		Infrastructural	▲	▲	▲	▲	▲	▲
E6	52		Environmental	▲	▲	▲	▲	▲	▲
B1	51		Social	▲	▲	▲	▲	▲	▲
F6	49		Environmental	▬	▬	▬	▬	▲	▲
B5	48		Technological/ SMART	▬	▬	▲	▲	▬	▬
D3	47	irrelevant	Legal	▼	▼	▼	▼	▲	▲
G1	36		Social	▲	▬	▲	▬	▬	▬
A3	31		Legal	▲	▲	▲	▲	▬	▬
C1	19		Social	▬	▬	▬	▬	▲	▲
B2	13		Economic	▬	▲	▬	▲	▬	▲
I1	3		Social	▲	▲	▲	▲	▲	▲

Source: authors' elaboration

▲ possitive impact (increasing the use)
▬ nagative impact (decreasing the use)
▼ no impact observed

Table 4. Ranking of innovative categories

Weight	Priority	Social	Economic	Legal	Infrastructural	Technological/ SMART	Environmental
4	high	18%	19%	24%	16%	14%	9%
3	medium	22%	23%	12%	0%	22%	22%
2	low	8%	21%	0%	41%	21%	9%
1	irrelevant	27%	3%	19%	13%	13%	25%
Total		100%	100%	100%	100%	100%	100%
Ranking		1.82	1.91	1.50	1.59	1.77	1.45

Source: authors' elaboration

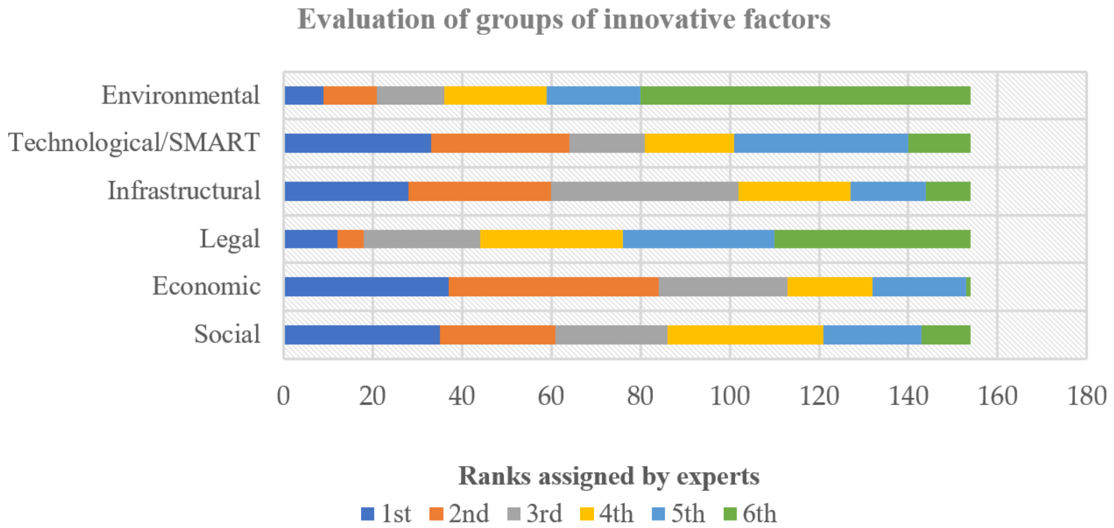


Fig. 6. Expert evaluation of groups of innovative factors
Source: authors' elaboration

Table 5. Group ranks in the evaluation

Group of factors	Social	Economic	Legal	Infrastructural	Technological / SMART	Environmental
Weight	0.19	0.21	0.13	0.19	0.18	0.11

Source: authors' elaboration

variance while simultaneously maximising between-group variance and meeting the requirement for the minimum number of objects in each group.

The first group includes Estonia, Greece, Hungary, Slovakia, Turkey and Romania. Most of them have a low level of GDP per capita in PPS, with only Estonia classified at the middle level (Fig. 7 and 8). The second group includes four countries, of which two (Bulgaria and Latvia) have a low level of GDP per capita in PPS, Slovenia has a medium level, and Finland a high level. The third group of countries is the most numerous (Fig. 7 and 8). It includes six countries with a high level of GDP per capita in PPS (Austria, Germany, Italy, Netherlands, Norway, Sweden) and four countries with a medium level (Czechia, Lithuania, Poland, Spain). Thus, it can be observed that the groups established based on cluster analysis do not fully align with the grouping of countries determined based on economic income data.

Based on the analysis, a list of innovative factors with the greatest impact on TB in the groups created using the Ward method was also determined (Fig. 9 a–d). In none of the groups did environmental factors appear.

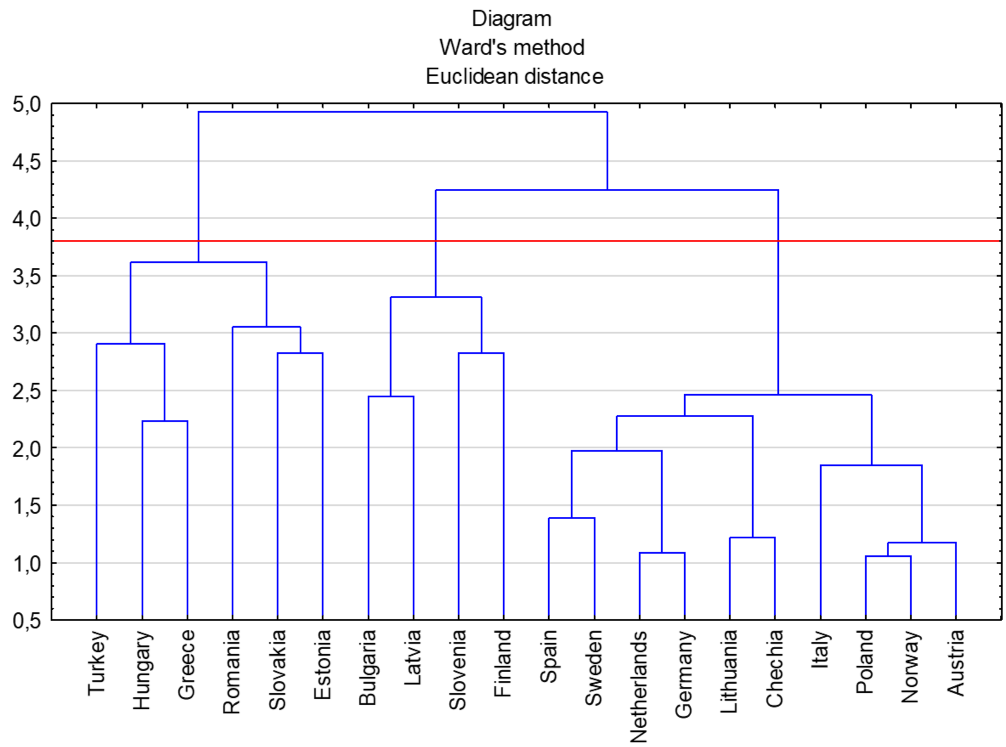


Fig. 7. Innovations influencing TB – Ward's method clustering
Source: authors' elaboration

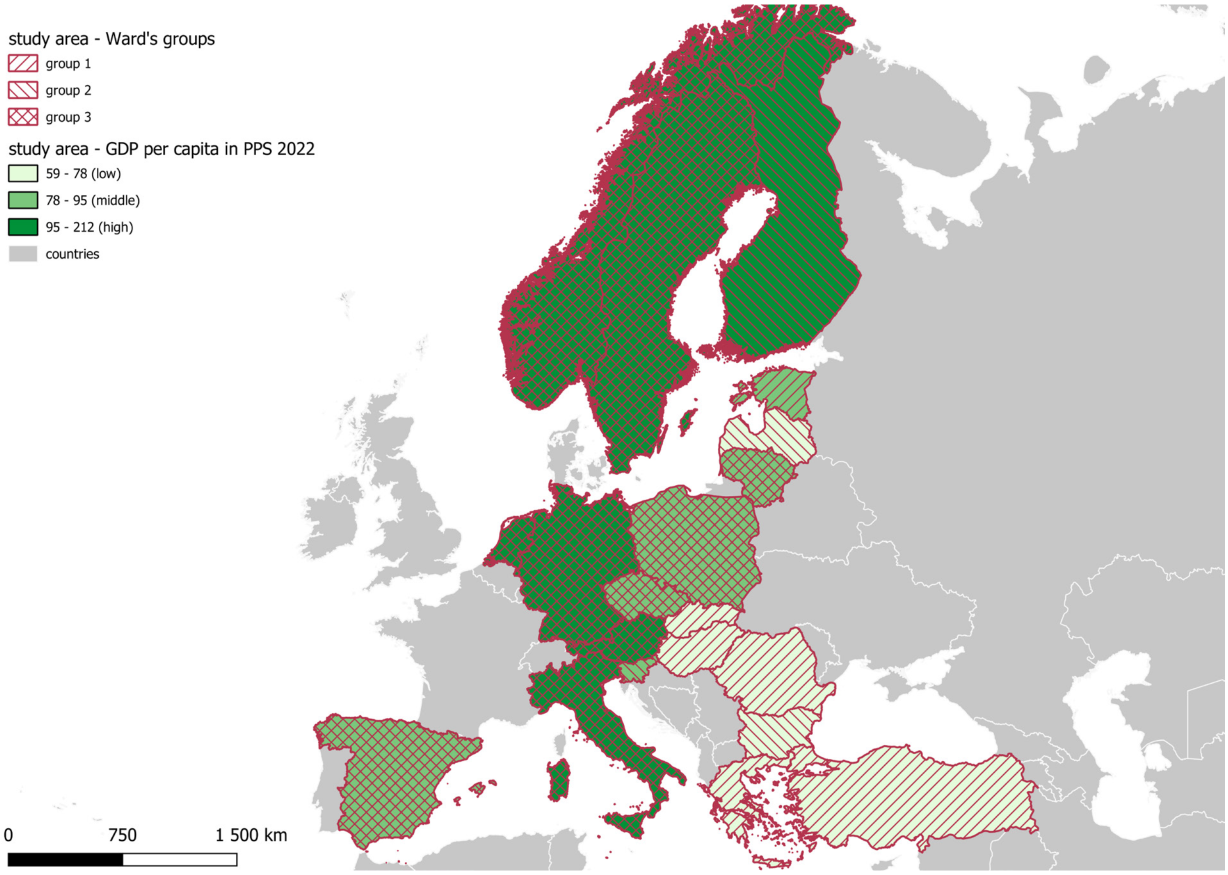


Fig. 8. Groups of countries - Ward method with GDP per capita in PPS
Source: authors' elaboration

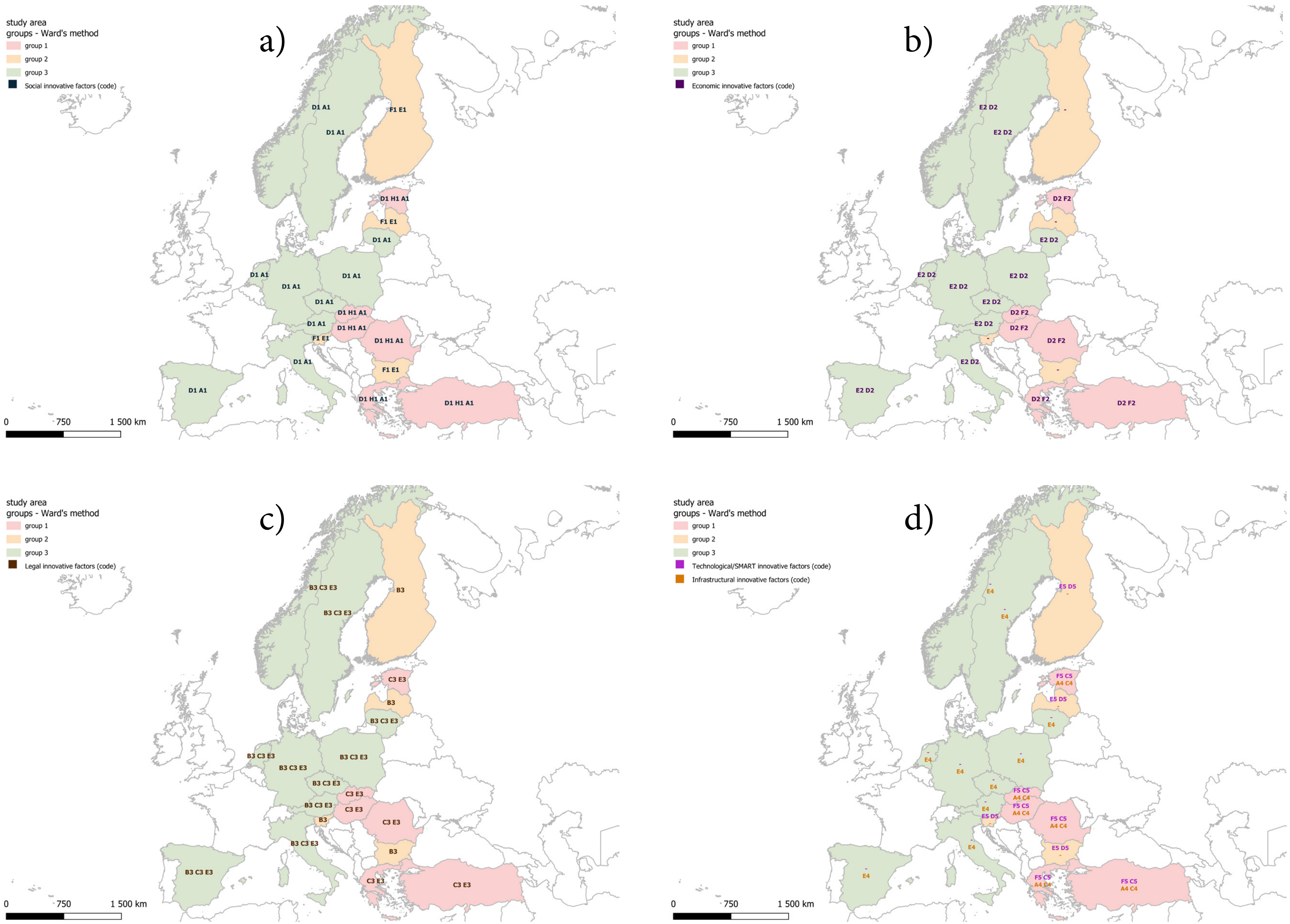


Fig. 9. High – impact innovative factors in Ward's groups of countries. Context: a) Social b) Economic c) Legal d) Infrastructural and Technological/SMART
Source: authors' elaboration

The first group was classified with 11 factors, making the list the most diverse. Among them are three social factors (D1 Less crowded public transport (bus, tram), H1 Higher travel comfort, A1 Remote work), two economic factors (D2 Higher service frequency, changes in public transport timetables, F2 Decrease in fuel/electricity prices), three legal factors (C3 Expansion of areas that are accessible to shared vehicles, E3 Introduction of legislation restricting or banning the use of high-emission vehicles (e.g., diesel) in cities or their parts), two infrastructural factors (A4 Construction of new roads, road upgrades, bike paths, etc., C4 New parking spaces or increased availability of parking spaces) and two technological/SMART factors (F5 Efficient traffic management system, C5 Innovative transport solutions, such as electric vehicles, kick scooters, scooters) (Fig. 9 a–d).

In the second group, there were only five high-impact factors. These are two social factors (F1 Eco-conscious attitude – public transport is chosen for environmental reasons, E1 Positive, passenger-friendly image of public transport – additional functionalities such as Wi-Fi, charging sockets, commuter trains, etc.), one legal factor (B3 Traffic calming in downtown areas – woonerf), and two technological/SMART factors (E5 Applications for tracking public transport vehicles, shared vehicles, and taxis – with the use of ITS and GPS tools; autonomous vehicles, D5 Travel planning applications) (Fig. 9 a–d).

In the third group, there are eight factors. Three of them come from the legal group (B3 Traffic calming in downtown areas – woonerf, C3 Expansion of areas that are accessible to shared vehicles (cars, bikes, scooters, etc.), E3 Introduction of legislation restricting or banning the use of high-emission vehicles in cities or their parts). Then, there are two social factors (D1 Less crowded public transport (bus, tram), A1 Remote work), two economic factors (E2 Discounts / special offers for public transport passengers / ticket sharing, D2 Higher service frequency, changes in public transport timetables) and one infrastructural factor (E4 Availability of transit hubs and park-and-ride (P&R) facilities) (Fig. 9 a–d).

It should be noted that none of the factors repeated in all three groups, and only five (A1, D1, D2, C3, E3) occurred in both the first and third groups, and only one (B3) occurred in both the first and second groups (Fig. 9 a–d). Table 6 summarises the high-impact innovative factors dividing them into the remaining groups. Only environmental factors were excluded, as none of the factors appeared in any of the groups.

4. Discussion

The respondents recognised the strong relationship between innovative solutions in various areas of life. Many of the indicated factors are also closely related to technological progress (including remote work, ticket sharing, and traffic management system). These solutions are rapidly gaining popularity in highly developed countries, and they significantly influence the existing or future transport policies in dynamically growing areas such as FUAs. The COVID-19 pandemic considerably accelerated the implementation of innovative solutions in other countries (Huang et al., 2023). The results obtained correspond to those (Campisi et al., 2021; Mavlutova et al., 2023) where the authors emphasise that smart and sustainable development of FUAs depend on the transportation system ensuring sustainable mobility.

However, in countries with low and medium GDP per capita in PPS (group 1), social factors dominate, while economic, legal, infrastructural and technological factors are equally represented. In countries with medium and high GDP per capita in

Table 6. High – impact innovative factors in Ward's groups of countries

Ward's group	Social	Economic	Legal	Infrastructural	Technological / SMART
1	**D1** H1 **A1**	**D2** F2	**C3** **E3**	A4 C4	F5 C5
2	F1 E1	none	**B3**	none	E5 D5
3	**D1** **A1**	**D2** E2	**B3** **C3** **E3**	E4	none

Source: authors' elaboration

PPS (group 3), legal, social and economic factors dominate, with infrastructural factors represented by only one factor. In the second group (encompassing countries with varying income levels), social and technological factors proved equally significant, with a marginal contribution from legal factors. Therefore, the prioritisation of factors does not depend on the level of GDP per capita.

Countries with higher GDPs usually have larger financial resources, enabling them to invest in research and development. Additionally, a high level of education, access to advanced technological infrastructure, and favourable conditions for entrepreneurship can contribute to an innovative environment. However, there are also examples of countries with lower GDPs that effectively foster innovation. The example of this is Poland, which is developing innovative strategies for mobility ("New Mobility Congress", 2023) and implementing them, even in the least affluent areas of FUAs, such as in the east of the country in FUA Olsztyn. The developed Sustainable Mobility Plan for the Functional Urban Area of Olsztyn 2030+ aims to further reduce the demand for individual transport, increase the share of environmentally friendly means of transport (*ZIT: Plan zrównoważonej mobilności dla MOF Olsztyna 2030+*, 2022) (e.g., public transport, bicycles, personal transport devices, pedestrian communication, electric vehicles), and at the same time, impact the reduction of the negative impact of transport on the environment, climate, and people (*ZIT: Plan …*, 2022). Another example is Lithuania, where a smart transport system is being progressively developed with particular support for smart card ticketing, e-ticketing, and state-of-the-art ticketing equipment (ticket vending machines (TVMs), card readers) (Jakubauskas, 2006). These actions support and strengthen programmes and national and EU policies focused on sustainable development. This often happens through specific strategies, public policies supporting innovation, the ability to attract foreign investment, flexible economic structures, and specific industrial or economic sector capabilities. Another example of the successful implementation of innovation in transport is from Hungary, namely the success of the BudapestGO! application introduced in the Hungarian capital that integrates various functions, including journey planning, ticket and pass sales and real-time information on the current status of public transport (*Farewell to FUTÁR, Hello BudapestGO!*, 2022). BudapestGO! provides users with instant access to digital tickets and passes, including tickets for a single trip, time-based tickets also repurchase passes and plan their public transport or cycling routes (*New features and faster operation on BudapestGO*, 2022). Meanwhile, in Latvia, new electric passenger trains have been implemented to contribute to cleaner transport under the project "Purchase of electric trains for the provision of the necessary urban and suburban passenger transport services by rail in Riga and Pieriga" through the "Growth and Employment" Operational Programme for the 2014–2020 programming period. The investment falls under the priority "Development of clean urban transport infrastructure" (*Inforegio – Latvia's new electric passenger trains to contribute to cleaner transport*, 2022).

The European Union consistently implements strategies and policies supporting innovations in transport. Key initiatives, such as the Mobility Strategy (*Communication from the Commission to the European Parliament, the Council, the European Economic And Social Committee And The Committee Of The Regions: Sustainable and Smart Mobility Strategy – putting European transport on track for the future*, 2020), promote a sustainable and future-oriented transport system, supporting electromobility and innovative transport services. Intelligent Transport Systems (*Intelligent transport systems – European Commission*, 2023) focus on the use of modern technologies to enhance travel efficiency and safety. The European Fund for Sustainable Development Plus (*European Fund for Sustainable Development Plus (EFSD+) – European Commission*, 2023) supports projects related to infrastructure and innovations in transport, contributing to sustainable mobility. The European Green Deal (*European Green Deal – Consilium*, 2023) focuses on climate neutrality, supporting innovations in transport, including electromobility. The EU Cohesion Policy includes support for transport infrastructure, public transport integration, and mobility balance between regions. The Horizon Europe programme funds innovative projects in transport, developing new technologies and mobility solutions. The Clean Vehicles Directive (*The Clean Vehicles Directive | European Alternative Fuels Observatory*, 2019) promotes low-CO_2-emission vehicles, supporting the development of the electric vehicle market. This is just part of the activities focused on promoting innovations in transport, reflecting the EU's commitment to sustainable and efficient mobility.

Therefore, it is important to create and update a list of innovations in transport systems in FUAs along with classification and ranking so that managers of these systems can implement selected solutions, aiming to improve them while simultaneously striving for sustainable development. These choices and their prioritisation will result from real needs, unaffected by the economic conditions of a given country but rather by the possibility of obtaining funds from external sources, primarily EU development programmes. In subsequent analyses of the usability of innovative solutions in transport systems of FUAs, their adaptation to the needs of different generations will be verified, especially Generation Y and Generation Z, who eagerly embrace technological novelties.

5. Conclusions

The expert survey revealed that a large number of the classified innovative factors influence TB in FUAs. According to the experts, the group of economic factors have the highest impact on the choice of transport modes in FUAs, but the four classification groups included factors from different categories in varying degrees of intensity (from high-impact to irrelevant factors). Therefore, not all factors should still be regarded as innovative.

The study results did not confirm the research hypothesis that the level of innovation utilisation in daily commuting to work and its impact on TB is similar across countries of similar levels of economic development. The study indicates that factors other than just the GDP per capita level could have an impact on innovation in transportation.

The results of the study were undoubtedly influenced by various barriers (security systems and legal restrictions) in the surveyed countries. The European Union consistently implements strategies and policies supporting innovations in transportation. In these countries, the regulatory frameworks for the transport sector contain different provisions relating to climate, infrastructure, information, culture, energy and landform. In some cases, these provisions offer temporary solutions to the problems and risks identified in the transport sector. The proposed approach for synthesising and standardising data is the main strength of the study.

However, the validation of the results of detailed analyses revealed that the identified innovative factors can have a different impact in other countries or regions (individual cases). The study also has several limitations. The present findings hold true only for the examined period because rapid socio-economic changes significantly affect TB. Travel behaviour could also be affected by a combination of overlapping factors, and the most influential factor may be difficult to identify.

Travel behaviour dynamics should be monitored and diagnosed in the local and international context by surveying other groups of passengers. Local diagnoses should involve spatial analyses to determine the location of factors whose spatial dimension can be measured (location and reach).

It is crucial to create and update a list of innovations in transport systems in FUAs, along with classification and assessment, so that managers of these systems can introduce selected solutions, aiming to improve them while simultaneously striving for sustainable development. Decision-makers are still characterised by low levels of situational awareness, and they do not make sufficient use of modern tools. Therefore, an algorithm for monitoring TB dynamics in FUAs in the context of transport innovations will be developed in successive studies conducted as part of this research project.

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