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Multi-Criteria Analysis in the Decision-Making Approach for the Linear Ordering of Urban Transport Based on TOPSIS Technique

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Abstract: The effects of urban transport are highly concerning. The rapid urbanization and motorization in smart cities have a huge impact on sustainability. The goal of the paper is to analyse the smart cities selected, in terms of the urban transport. This paper presents an overview of research works published between 1991 and 2020 concerning urban transport and MCDM (multi-criteria decision making). The author highlights the importance of decision-making criteria and their weight, as well as techniques. Seven criteria and forty-four objects were used as the input of the approach. The entropy weight method was used to compute the weight of each criterion. The TOPSIS (Technique for Order Performance by Similarity to Ideal Solution) was applied to calculate the assessment and ranking of transport performance for each smart city. Portland was found to be the best location for transport enterprises and projects; Tbilisi was ranked last. The values of the relative closeness coefficient ranged from 0.03504 to 0.921402. Finally, some suggestions for future research are discussed.

Keywords: urban transport; smart cities; ISO 37120's indicators; multi-criteria decision making

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1. Introduction

Urban transport should facilitate movement and access to public services. Mobility affects the life quality of the inhabitants and the sustainability of the city. Urban transport causes many problems, such as traffic congestion, greenhouse gas emissions, air pollution and noise, biodiversity loss, fatalities and injuries, increased fuel consumption, low mobility, reduced quality of life, and delivery delays [1]. Many cities are implementing sustainable mobility measures to improve the flow of passenger and goods, for example, energy-efficient vehicles, biofuels, cycling, walking, public transport, carsharing, park-and-ride, travel reduction, and distance reduction [2]. In order to mitigate climate change, reducing greenhouse gas emissions from transport is key to keeping the liveability of cities [3]. According to the European Commission forecasts, the intensity of freight transport in cities will increase by 40% by 2030, and rise by over 80% by 2050, when compared to 2005. At the same time, it is expected that passenger transport will also increase by approximately 34% by 2030, and by more than 50% by 2050, in comparison to 2005 [4].

Transport faces many challenges related to sustainability. Nowadays, transport emissions represent around 25% of the EU's total greenhouse gas emissions [4]. In 2011, a White Paper recommended a 20% reduction in transport emissions between 2008 and 2030, as well as at least 60% between 1990 and 2030 [5]. It also suggested the halving of the number of conventionally-fuelled cars in urban transport by 2030, with their complete phasing-out by 2050. The European Union encourage cities to develop sustainable urban mobility plans that prioritize low-carbon transport models, alternative fuel vehicles, and smart transport systems. It is anticipated that the EU's goal of at least a 55% greenhouse gas reduction by 2030, and that of climate neutrality by 2050, will be achieved [5]. Additionally, the transport sector represents 5% of European GDP and employs more than 10 million people in Europe [6].

There are a small number of decision-making study cases from the aspect of competitiveness and sustainability, related to urban transport. In empirical study, it is necessary to assess the solutions for traffic organisation and urban performance. The goal of this paper is to present the rankings of 44 smart cities around the world related to urban transport performance, based on the MCDM technique using seven criteria from the ISO 37120 standard. Firstly, the study identified publications on urban transport and MCDM based on a literature review. Secondly, it attempted to organize the techniques and main criteria in the field of urban transport and MCDM. The papers available on the Web of Science, Springer, Scopus, and Elsevier databases were reviewed. In the theoretical part, inductive thinking was used, whereby the empirical part was based on the TOPSIS technique and entropy method. The empirical part of article was tested on cities with ISO37120 standard. The implemented research indicated the possibility to evaluate the urban transport systems by using the TOPSIS technique for decision making. The paper is an attempt to answer the research questions: How can we measure the urban transport performance from the point of view of city residents' transport needs and the quality of life, as well as, what does the classification of the smart cities present, in terms of urban transport, look like?

The MCDM technique was chosen because it avoids pairwise comparison, thus allowing it to be calculated in a simple and efficient way. Ranking a number of feasible alternatives based on the closeness to the ideal solution is best achieved by the TOPSIS approach. TOPSIS is a compensatory aggregation technique based on the idea that the ideal alternative must the smallest geometric distance to a positive ideal solution, and the geometric farthest distance to a negative ideal solution. It means, the benefit is maximized and cost is minimized. There is no study, despite growing interest in the issue, which includes a comprehensive and complete set of criteria characteristics for the urban transport based on the ISO 37120 standard. Considering this important gap in the literature, this paper aims to contribute on location theories by providing a framework based on problem hierarchy and the use supporting tools from the multi-criteria decision. It is a tool designed for city leaders. This framework can be used for different needs or multi-criteria problems faced by the cities. There are several other reasons for applying the TOPSIS techniques for this case study. (1) It is based on quantitative data. (2) It allows the possibility of performing calculations in a regular spreadsheet. (3) The TOPSIS techniques enable identification of patterns and anti-patterns.

The paper is organized into six sections and four appendixes. Section 1 provides an introduction to urban transport, while Section 2 presents a literature overview on MCDM techniques and criteria in urban transport. Section 3 describes the research methodology, while Section 4 presents an overview of research criteria and profiles of objects. Section 5 includes the smart cities ratings and an assessment of urban transport. Section 6 provides some general conclusions. Appendices A and B contain the results of a review of the following databases such as Web of Science, Springer, Scopus, and Elsevier in the context of urban transport and MCDM techniques. Thus, the third and fourth appendixes contain examples of the conducted research results (Appendices C and D).

2. Literature Review

Recently, many studies have explored the assessment of urban transport performance. Researchers often use technical efficiency, total factor productivity, and service satisfaction to evaluate the urban transport performance [2]. Researchers establish public transit service as production, such as vehicle-kilometres, passenger-kilometres, employees, fuel, and number of vehicles [3]. The transit performance assessment depends on inputs (capital, labour, energy, and air pollution) and outputs (gross domestic product, and GDP). MCDM techniques are a useful tool for measuring urban transport performance. The selection was performed on the basis of a cost–benefit analysis. Classical economic analysis techniques are unable to take into account the non-monetary parameters, which have a large impact on the result. The application of MCDM techniques allows the comparison of non-homogeneous criteria and prepare the ranking of the different alternatives. The TOPSIS technique is characterized by its simplicity and the computation process is a simple mathematical form. The decision-making process allows to search the best alternatives for each criterion.

The author analysed publications with the implementation of at least one MCDM technique to solve the problem related to urban transport. Papers available on the Web of Science, Springer, Scopus, and Elsevier databases were reviewed (Appendix A). Figure 1 presents the chronological evolution of the number of publications published for the period 1991 to 2020. More than 22,000 papers were published over the last three decades. There was a significantly increasing trend of growth each year. Additionally, an exponential increase in the number of papers has been observed since 2006. Most of the papers were observed in the Scopus database.

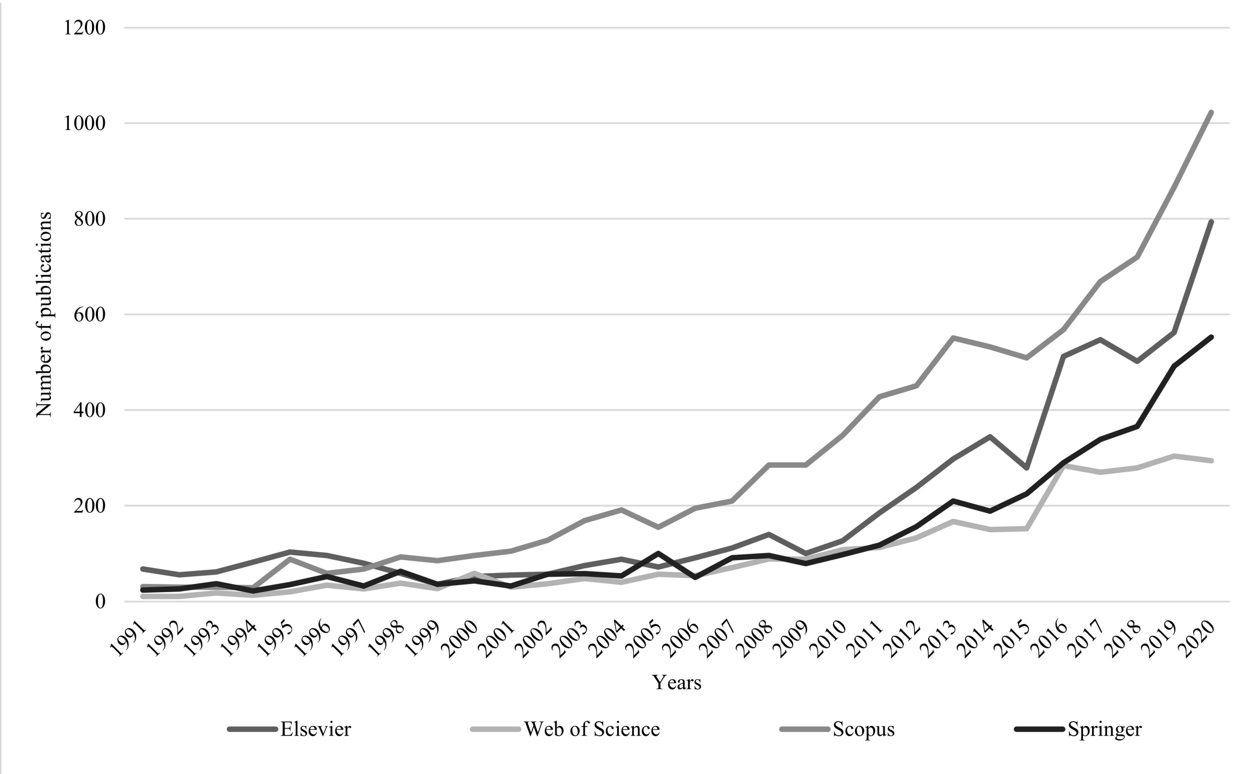

Figure 1. Number of publications on the topic urban transport published over the period 1991–2020 (status: 2 October 2021). Source: author's work.

Decision making is a common human practice that requires choosing the best alternative among many. MCDM techniques are considered the modern part of operations research with the multi-objective optimization problem. One of the first publications on MDCM was performed by Benjamin Franklin in his work on moral algebra. Since the 1950s, MCDM has been practiced by theoretical and empirical scientists to test the capability of mathematical modelling of decision-making approaches. The MCDM provides a framework for structuring decision problems and provides a set of methods for generating preferences among alternatives. Their advantage is the ability to take into account the contradictory and disproportionate effects of the decisions. The limitation is that the generated solutions are a compromise between many goals and are not optimal due to the nature of the problem.

The next stage analysed the publications regarding the MCDM techniques related urban transport (Figure 2). Over fifteen different MCDM techniques were used (Appendix B). "Transport Policy", "Transport Research Part A: Policy and Practice", and "Applied Soft Computing" are the top journals referred to urban transport and MCDM techniques. In a review of the research paper, the author observed that AHP (Analytical Hierarchy Process) is the most popular MCDM technique [7]. DEA (Data Envelopment Analysis) and

TOPSIS are the well-known classical MCDM techniques. Authors used the lower proportion ELECTRE (Elimination et Choice Translating Reality), PROMOTHEE (Preference Ranking Organization Method for Enrichment Evaluation), or VIKOR (Vlsekrzterijumska Optimizacija I Kompromisno Resenje). In addition, MACBETH (Measuring Attractiveness by a Categorical Based Evaluation Technique), DEMATEL (Decision Making Trial and Evaluation Laboratory), and REMBRANDT (Ratio Estimation in Magnitudes or deci-Bells to Rate Alternatives which are non-dominated) are also considered. A lot of papers used two or more MCDM techniques (hybrids) [2,8–15].

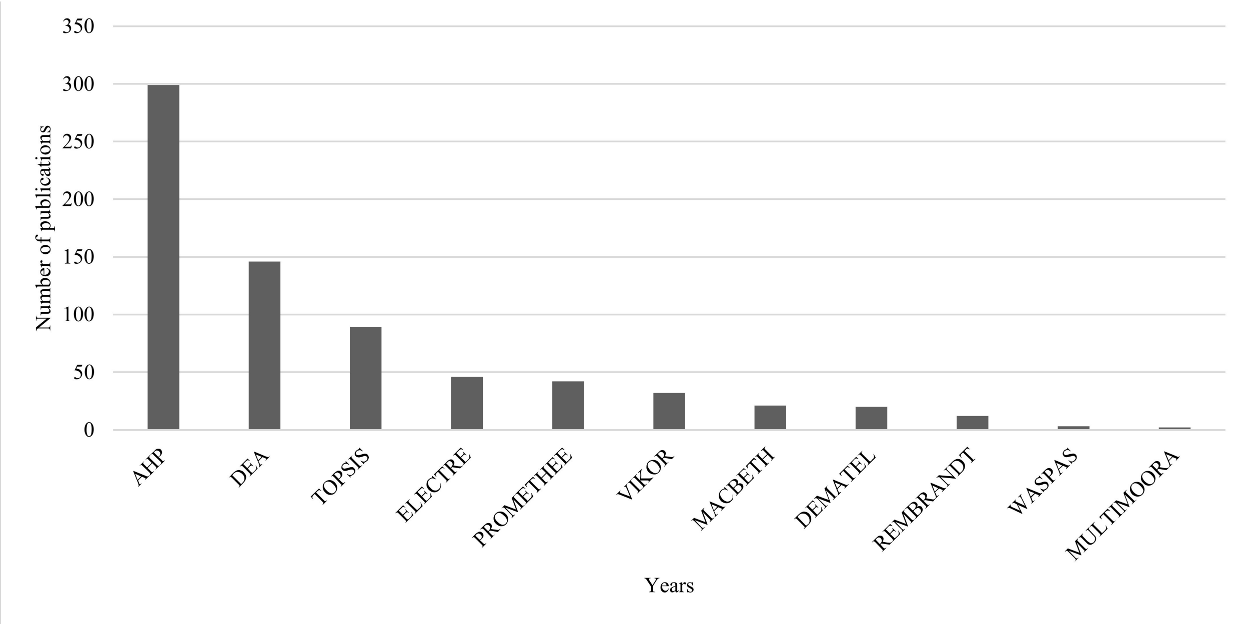

Figure 2. Number of times that the different MCDM techniques were employed in the reviewed publications in the field urban transport (status: 4 October 2021). Source: author's work.

The highest number of published papers concern the evaluation of the performance of urban transport. MCDM techniques are advantageous in comparison with the classical assessment methods, focussing on a single criterion such as cost–benefit analysis. The MCDM techniques are the most used, mainly for the choice of infrastructure, information systems technologies, choice of clean technologies for vehicles, location problems, and choice of transportation mode and route.

The identification of the best alternatives is highly dependent on the criteria and their weighting [8]. Criteria should be independent of alternatives and relevant to the decision-making process. Perez et al. argue that economic, logistic, and technical criteria were considered in early papers, while environmental and social criteria have been considered more recently [9]. Economic criteria are related with financial resources, for example, implementation costs, GDP, transportation expenses, infrastructure investments, maintenance costs, taxes, operational costs, and fuel costs. Logistic and technical criteria refer to technical requirements such as travel time, demand, number of vehicles, accessibility, reduction in journeys numbers, transit flows, transportation mode, technical feasibility, system reliability, and efficiency of the transport network. This criteria affect the economic issues of transport. Environmental criteria consider the impact on the natural environment, for example, energy efficiency, fossil fuel consumption, use of natural resources, the level of carbon emissions, GHG emissions, and ecological use. Safety criteria are associated to safety passengers and users involved in the operations of transport systems, such as transit accidents, fatalities, pedestrian safety, health risk, and reduction in consequences of accidents. These criteria could be included as a part of social criteria. Social criteria include consumer satisfaction, social equity, corporate social responsibility, participation of the population in decision making, preference of society regarding transport alternatives, people adaptability to the transport system, and society welfare. Land-use criteria refer to the location of activities. Miskolczi et al. argue that role of automation, sharing mobility, electric vehicles, congestions, GHG emissions, and social attitudes are the future topics in the context of urban transport [10].

The author conducted the literature review that focused on MCDM techniques in the field of urban transport. The summary indicates the aims of each paper, objects, MCDM techniques, and main criteria of the research. Table 1 presents the results of this analysis.

Table 1. Papers relevant to MCDM and urban transport.

Authors	Kind of Methods	Aims	Objects	Criteria
Feizi, Joo, Kwigizile, Oh [11]	TOPSIS	To assess transportation performance measures and smart growth of cities	46 cities in the U.S.	4 groups of criteria: network performance, traffic safety, environmental impact and physical activity
Zhang, Zhang, Yuan, Wang [16]	Entropy-TOPSIS	To evaluate the economic, social, and ecological impact of transportation network in urban agglomeration	13 cities of Beijing–Tianjin–Hebei region	Economic (fixed assets investment in transport, storage, and post, gross output value of transport, storage, and post, passenger traffic, freight traffic), society (population density, employment in transportation industry, length of roads, urbanization rate), and ecology (noise, PM_{10}, SO_2, NO_2) impact assessment of transportation network
Samaie, Javadi, Naimi, Farahani [17]	fuzzy TOPSIS	To evaluate environmental policymaking based on sustainable development to increase the penetration of electric vehicles	plug-in hybrid electric vehicles in Teheran	nature (CO emission, NOX emissions, CO2 emissions, worn-out vehicle recycling system, noise, life cycle assessment), economic (vehicle cost, maintenance cost, fuel price, number of vehicle manufacturers, cost of battery, technology life cycle), social (age structure, mortality rate, vehicle size), system (technical knowledge at national level, charging time, voltage imbalance index, overall efficiency of vehicles)
Sinniah, Li, Abdulkarim [18]	fuzzy TOPSIS	To assess public transportation competitiveness in term of the bus system based on a self-evaluation framework	Johor Bahru city, Malaysia	Infrastructure (facilities for disable, bus schedule notice, bus station location, bus operating location, bus operating frequency, safe environment in bus coach, security system of transport system, safety of bus station), accessibility (public transportation network coverage ratio, supply ability during peak-hour), perception (bus fare, real-time information, travel journey)

Table 1. *Cont.*

Authors	Kind of Methods	Aims	Objects	Criteria
Tang, Li, Gao, Zong [19]	TOPSIS and Weighted Closeness Centrality	To identify critical nodes in public transport network	Metro and bus network in Shenzhen, China	Global efficiency, the size of the largest connected component
Sinniah, Li, Abdulkarim [18]	fuzzy TOPSIS	To assess public transportation competitiveness in term of the bus system based on a self-evaluation framework	Johor Bahru city, Malaysia	Infrastructure (facilities for disable, bus schedule notice, bus station location, bus operating location, bus operating frequency, safe environment in bus coach, security system of transport system, safety of bus station), accessibility (public transportation network coverage ratio, supply ability during peak-hour), perception (bus fare, real-time information, travel journey)
Tang, Li, Gao, Zong [19]	TOPSIS and Weighted Closeness Centrality	To identify critical nodes in public transport network	Metro and bus network in Shenzhen, China	Global efficiency, the size of the largest connected component
Tudela, Akiki, Cisternas [20]	AHP utilising 2 approaches to derive the weights	To compare the outcome of cost benefit analysis and a multi-criteria method	2 alternative of transport project	Benefits: economic (travel time saving, fuel saving, operation cost reduction, delays reduction crossing), environmental (accident reduction, better accessibility) Costs: economic (investment, maintenance), environmental (noise, air pollution, visual intrusion)
Wolnowska, Konicki [21]	AHP	To evaluate the transport route variants to be used for transport of oversize cargo	3 route variants through the city Szczecin	Transport means selection, impact on road infrastructure and engineering objects, impact on tramway power grid, impact on inhabitants' quality of life, impact on urban greenery, transport costs
Vajjarapu, Verma [22]	AHP	To assess the urban transportation system's adaptability to urban flooding	3 adaptation policy bundles designed to improve the urban transportation system's resiliency in Bangalore, India	Environmental pillar: exposure (maximum annual rainfall, monthly rainfall, rainy days, concrete area), resilience (water bodies density, vegetation density) Social pillar: resilience (vehicle hours travelled, average speed of the vehicle, average trip length, cancelled trips, vehicle kilometres travelled) Economic pillar: susceptibility (roads in low lying areas, total vehicles, Gross District Domestic Product growth rate)
Sancha, Mayoral, Román [23]	DEA	To assess of transit transfer stations efficiency using technical, social, environmental variables	36 transit transfer stations located in Mexico City Metropolitan Area	Input: transfer area, bus platform length, automatization; connectivity, capacity, transfer index; CO_2 emissions, BC emissions, energy consumption Output: demand, user's satisfaction

Table 1. *Cont.*

Authors	Kind of Methods	Aims	Objects	Criteria
Suguiy, Carvalho, Nithack e Silva [24]	DEA	To evaluate the urban public transport systems under 3 objectives: infrastructure efficiency, service level, city efficiency score	49 Brazilian cities, which include more than 300,000 inhabitants	56 indicators in 9 themes: citizenship and social assistance, health and culture, sport, work and income, public safety, public finances, basic sanitation, transport, transit
Pamucar, Deveci, Canitez, Bozanic [25]	Fuzzy Full Consistency Method-Dobi-Bonferroni model	To select and prioritize of appropriate Transport Demand Management	Istanbul's urban mobility system	Capital costs, operating costs, travel time, public transport trip revenues, social inclusion, vulnerable users, public opposition, decreasing carbon emissions, fuel saving
Liu, Tzeng, Lee, Lee [12]	DEMATEL, DANP, VIKOR	To examine the connection service between metro systems with urban airports	Taipei MRT to the Songshan Airport in Taiwan	3 dimensions and 10 criteria: service quality (tangibles, reliabilities, responsiveness, assurance, empathy), satisfaction (service attributes, service encounters, emotional judgement), behavioural intentions (recommendation, reride)
Curiel-Esparza, Mazario-Diez, Canto-Perello, Martin-Ulrillas [13]	AHP, VIKOR	To select the optimal alternative in terms of sustainable mobility	The main transport in Valencia	Economy: initial costs, operation, environmental; Travel quality: time, comfort, trip cost; Sustainability: pollution, noise, carbon footprint, health
Lambas, Giuffrida, Ignaccolo, Inturri [26]	TOPSIS	To compare and determine a global score of public transport systems	Light-Rail Transit (tramway) of Santa Cruz of Tenerife in Spain and Bus Rapid Transit of Prato in Italy	Transport impact (safety, security, accessibility, travel cost, integration, flexibility, capacity, reliability), economic impact (infrastructure cost, operating and maintenance costs, vehicle purchasing costs, profitability), social impact (community severance, land use, comfort), environmental impact (energy consumption, noise pollution, air pollution)
Sobhani, Imtiyaz, Azam, Hossain [14]	AHP-TOPSIS	To identify of factors affecting sustainability and competitiveness of unconventional modes of transport	3 unconventional modes of transport (rickshaw, leguna, easy bike) in Dhaka the capital of Bangladesh	Political (political stability, government policy), economic (duties and taxes, economic growth, unemployment, cost efficiency), social (health, safety, security), technology (operation and maintenance, fuel efficiency), legal (ban, restricted movement), environment (noise pollution, air pollution)
Taboada, Han [27]	DEA, Exploratory Data Analysis	To assess the efficiency of transport modes	10 lines of Transport for London Urban Rail Transit	Input: overall cost, CO_2 emissions (undesirable), number of stations, weekly frequencies Outputs: number of passengers

Table 1. *Cont.*

Authors	Kind of Methods	Aims	Objects	Criteria
Budimir, Šoštarić, Vidović [28]	DEA	To evaluate the transport system efficiency	Transport network of the City of Makarska	Input: coefficient of number of vehicles on entrance and exit points (controlled parameter) Output: coefficient of traffic flows intersections (interdependent variables, information)
Fitzová, Matulová, Tomeš [29]	DEA	To identify the factors influencing efficiency of urban public transport systems	19 urban public transport systems in the Czech Republic	Input: vehicle-kilometres, number of employees, number of vehicle, material and fuel costs, length of lines Outputs: total number of passengers
Singh, Singh, Singh, Kumari, Sangaiah [30]	DEA	To assess and design a socially efficient public transport bus routes	24 public transport bus routes for the Allahabad city of Uttar Pradesh state, India	Route length, population along route
Zhang, Zhang, Sun, Zou, Chen [31]	structural entropy TOPSIS	To evaluate public transport priority performance	Wuhan city	Overall development level, infrastructure construction, public transport service, policy support
Zhao, Zhou, Li, Yang, Zhou [32]	Entropy-weighted TOPSIS	To analyse the impact of different capacity parameters on the layout of the network	14 Shanghai's metro stations	Number of spoke nodes, number of parcels per day at demand point, distance between demand point and spoke node, maximum service radius of the spoke node, parcel-handling capacity of spoke node
Awasthi, Omrani, Gerber [2]	TOPSIS, VIKOR	To evaluate of urban mobility projects	3 mobility projects in Luxemburg city	economic: revenues, investment costs, operating costs, travel cost; environmental: fossil fuel consumption, GHG emissions, local pollutants, noise; social: number of potential users, social equity, impact on city congestion reduction, land consumption by the project, impact of transport project on land use, number of private cars replaced, number of public parkings replaced; technical: travel time between locations, reachability to major locations, service reliability, spatial accessibility, frequency of transport, service area network, connectivity to multimodal transport, park and ride facility, safe, security, vehicle occupancy, suitability to disable customers, modern and clean facilities, staff service quality, integration with ICT, possibility of network expansion

Table 1. *Cont.*

Authors	Kind of Methods	Aims	Objects	Criteria
Sinha, Sadhukhan, Priye [33]	TOPSIS	To assess the quality of services of midi buses in terms of user satisfaction based on experiences while commuting	midi buses in Patna, India	Bus being on time, cleanliness of bus, condition of bus stop, condition of bus, smoothness of ride, easy to carry luggage, crowding condition, relatively cheap fare, convenient fare, bus route selection, driver's behaviour, ticketing facility, comfort facility
Huang, Shuai, Sun, Wang, Antwi [1]	TOPSIS	To evaluate the urban rail transit system's operation performance from the operator's, passenger's and government's perspective	Chengdu subway	Networks, stations, passenger, train operation, service, safety, energy, cost indicators
Aljohani, Thompson [34]	TOPSIS	To characterise suitable locations for an inner-city consolidation facility based on spatial aspects, operational requirements, and societal concerns	Inner Melbourne, Australia	Warehouses, parking locations, demographic attributes, land-use zones, major roads, traffic intensity, access restrictions, facility rental costs, major receivers, bike lanes, impact to residents
Jakimavičius, Burinskiene, Gusaroviene, Podviezko [15]	AHP, SAW, TOPSIS	To rank alternatives and to make a comparison of the obtained calculation results	6 rapid bus routes in the network of Vilnius public transport	Rapid bus lines supply, average speed, monthly expenses, number of citizens in transport zones, number of work places in transport zones, number of bus trips in the route per month, passengers per month
Shen, Zhao, Fang [35]	TOPSIS	To analyse the development of green transport	Zhoushan city in China	basic indicators: population, annual average wage of on-the-job employees, GDP; vehicle: large and medium sized cars, small cars, other vehicles, motorcycles, motorized fishing boats; road construction: road length, road area, green coverage area

Source: author's elaboration on the basis of [1,2,11–35].

Based on the literature review, the author identified several areas of urban transport: (i) mobility performance, (ii) sustainable transport assessment, (iii) transport efficiency, and (iv) safety on the road. The urban transport studies are orientated to a different type of city, such as sustainable, liveable, competitive, and smart. The interest in the problem of urban transport evaluation is high and constant. The urban transport studies include four perspectives: rail transport, road network, shared transport, and external connectivity. The sustainable transport assessment obtains low-carbon performance, well-being performance, security performance, and carbon emission performance. While, the mobility performance involves the following metrics such as availability, affordability, and convenience. The transport efficiency can be analysed in two dimensions, public and personal transport.

Sancha et al. claim that medium size transit transfer stations are more suitable to reach a better balance among technical, social, and environmental objects [23]. However, Pamucar et al. show that public transport capacity improvements are the best alternative among the other transport demand management measures [25]. Sobhani et al. suggest that economic, social, and political factors have the highest influence on sustainability and competitiveness of unconventional modes of transport [14]. Additionally, Taboada et al. claim that Exploratory Data Analysis and Data Envelopment Analysis play a key role in improving decision making in transport network management and route planning. Techniques are useful to score multiple transport modes and Urban Rail Transit lines efficiency [27]. Fitzová et al. argue that bigger cities with greater population densities are more efficient than smaller cities, and the main efficiency factors are the ticket price, rate of subsidies, and structure of the city transport system [29]. Moreover, Singh et al. proposed methodology useful for developing a bus route transportation network for city using multimodal GIS data and social priority [30]. Awasthi et al. argue that a new tramway in the city centre of Luxembourg is the best alternative for implementation [2]. Likewise, Sinha et al. suggest that users are satisfied with ticketing facility, seat comfort, condition of bus stops, and condition of bus, whereas dissatisfaction was found for bus information at the bus stop, frequency of bus service, and buses not being on time [33]. Shen et al. suggest strengthening the construction of urban road transportation systems, optimizing transportation, improving the infrastructure of new energy vehicles, and promoting the concept of green transportation [35]. One of the most important things that has a significant impact on urban transport is the stakeholder participation. There are business and service operators, citizens, as well as authorities, who have different goals and perspectives [36,37]. Additionally, Queiroz et al. claim that smart mobility systems in city provide opportunities for the well-being of citizens and permit the solving of problems arising from the impacts of urbanization [38]. Fistola proposed that urban mobility meant distribution, quality, and use of urban activities with ICT, as well as different users being required [39].

Transport is one of smart city's dimensions in the rankings. Table 2 presents the characteristics of the most popular smart cities rankings.

Table 2. The characteristics of the most popular smart city rankings.

Name	Organization	Objects	Best cities	Dimensions
Global Smart City Index [40]	Institute for Management Development, World Competitiveness Centre, Singapore University for Technology and Design	109 cities	Singapore, Helsinki (Finland), Zurich (Switzerland)	Priority areas (affordable housing, fulfilling employment, unemployment, health services, basic amenities, school education, air pollution, road congestion, green spaces, **public transport**, recycling, security, citizen engagement, social mobility, corruption), attitudes, structures, technologies (health and safety, mobility, activities, opportunities, governance)
Cities in Motion Index [41]	IESE University of Navarra Business School	174 cities (79 capitals) in 80 countries	London (UK), New York (USA), Paris (France)	101 indicators in 10 key dimensions: economy, public management, social cohesion, human capital, international projection, technology, urban planning, **mobility and transportation**, environment, governance
TOP50 Smart City Governments [42]	Eden Strategy Institute	50 cities	London (UK), Singapore, Seoul	factors: vision, leadership, budget, financial incentives, support programmes, talent-readiness, people-centricity, innovation ecosystems, smart policies, track record

Table 2. *Cont.*

Name	Organization	Objects	Best cities	Dimensions
Global Power City Index [43]	Institute for Urban Strategies, The Mori Memorial Foundation	48 cities	London, New York, Tokyo	70 indicators in 7 areas: economy, research and development, cultural interaction, liveability, environment, accessibility
Smart Cities Index [44]	EasyPark Group	100 cities	Copenhagen, Singapore, Stockholm	**Transport and mobility**, sustainability, governance, innovation economy, digitalisation, cyber security, living standard, expert perception
Global Cities Index [45]	A.T.Kearney	128 cities	New York, London, Paris	Business activity, human capital, information exchange, cultural experience, political engagement
Global Liveability Index [46]	Economist Intelligence Unit	140 cities	Vienna, Melbourne, Sydney	Stability, healthcare, culture and environment, education, **infrastructure**
Innovation Cities Index [47]	2THINKNOW	500 cities	Tokyo, London, San Francisco	Cultural assets, human infrastructure (**transport**, universities, government, technology), networked markets (location, military, economies of related items)
City Competitiveness Index [48]	Economist Intelligence Unit	120 cities	New York (USA), London (UK), Singapore	32 indicators in 8 categories: economic strength, **physical capital**, financial maturity, institutional effectiveness, social and cultural character human capital, environmental and natural hazards, global appeal
Quality of Living City Ranking [49]	Mercer	498 cities worldwide	Vienna (Austria), Zurich (Switzerland), Vancouver (Canada)	39 factors in 10 categories: consumer goods, economic environment, housing, medical and health considerations, natural environment, political and social environment, public services and **transport**, recreation, schools and education, socio-cultural environment
Global cities in Harmonious Development [50]	Geography Department at Loughborough University, Globalization and World Cities (GaWC)	707 cities in categories alpha, beta, gamma cities	London (UK), New York (USA), Hong Kong	International connectedness based on accountancy, advertising, banking/finance, law
Sustainable Cities Index [51]	Arcadis	100 global cities	London, Stockholm, Edinburgh	People (health, education, crime, income inequality, working hours, dependency ratio, **transport accessibility**), planet (water supplies, sanitation and air pollution), profit (rail, air and **traffic congestion**, GDP, mobile and broadband connectivity)

Table 2. *Cont.*

Name	Organization	Objects	Best cities	Dimensions
European Digital City Index [52]	Nesta, European Digital Forum	60 cities	London, Stockholm, Paris	Access to capital, business environmental, digital infrastructure, entrepreneurial culture, knowledge spillovers, lifestyle, market, mentoring and managerial assistance, **non-digital infrastructure**, skills

Legend: the bold type means dimensions related to transport. Source: author's elaboration on the basis of [40–52].

The literature contains many procedures for testing a city's performance, such as The Smart City Index [44], The Innovation Cities Index [47], The Global Smart Cities Index [40], The City Competitiveness Index [48], The Global Liveability Index [46], and The Sustainable Cities Index [51]. Numerous organizations and institutions have prepared city rankings, in particular, relating to the life quality, innovation, competitiveness, such as the Institute for Urban Strategies [43], Mercer [49], the Institute for Management Development [40], and Arcadis [51]. Conger prepared an overview of the indexing methodology [53]. Dameri argued that the process of evaluating sustainable smart cities is a complex task [54,55]. Furthermore, Sacirovic et al. introduced a transformation between the present and the vision of a sustainable city in the future [56].

The determinants of a high position in the cities ranking are digital services associated with public transport and investments in low-carbon transport infrastructure, including bike sharing and electric incentives. Cities that promote energy-efficient public transport can reduce the city's ecological footprint. Moreover, the most popular smart city rankings use the following metrics in related to transport such as: travel comfort, electronic services, intermodality, and a ticketing system [57]. Mobility innovation can be measured by traffic management, clean transport, and parking innovation [44].

TOPSIS technique is often used in urban transport. Moreover Zhang et al. established an index system to evaluate public transport priority performance by comprehensively considering four subsystems such as overall development level, infrastructure construction, public transportation level, and policy support [31]. Huang et al. evaluated the urban rail transit system's operation performance from the operator's, passenger's, and government's perspectives [1]. The number and the frequency of the operation accidents of the network are the most important sub-indicators in the evaluation system. Ajith et al. developed a framework for the selection of the best chassis among original equipment manufacturer based on the following criteria: technical features, cost of ownership, operational characteristics, reliability, maintenance, and safety [58]. Likewise, Awasthi et al. presented a multi-criteria decision-making approach for sustainability assessment of urban transportation systems [59]. There criteria are operating costs, safety, security, reliability, air pollutants, noise, GHG emissions, usage of fossil fuels, travel costs, waste from road transport, energy consumption, land usage, accessibility, benefits to economy, mobility, occupancy rate, share in public transit, and convenience to use. Alternatively, Sobhani et al. presented a framework to assess the sustainability and competitiveness of unconventional modes of transport in developing cities. The major driving forces in this market are economic, political, and social factors, with legal factors also exhibiting a weak influence [14]. Sinha et al. assessed the quality of services of midi bus users in terms of satisfaction based on their experiences while commuting [33]. Satisfaction was found for ticketing facility, seat comfort, condition of bus stops, and condition of bus, whereas bus information at the bus stop, frequency of bus service, and buses being on time are big concerns for the users. In addition, Zhao et al. evaluated the importance of each metro stations by complex network theory [60]. Erdogan et al. carried out a prioritization analysis for failures of corrective actions in Bus Rapid Transit system [61]. The most important failures were engine or fuel injection malfunction, whereas smart ticket machine failure was the least important. However, Buyukozkan et al. evaluated different public bus technologies as urban transportation alternatives. Dependencies among decision criteria significantly affect the selection process of the most sustainable urban transportation systems [62]. Zhu et al. established a comprehensive evaluation indicator system of metro development conditions [63]. The metro systems of slightly unbalanced cities should put urban development first because only favourable demand and supply conditions will benefit the metro development. Moreover, Shen et al. suggested the promotion of the development of green transportation from four aspects: strengthening the construction of urban road transportation system, optimizing transportation, improving the infrastructure of new energy vehicles, and promoting the concept of green transportation [35]. Lambas et al. compared Light-Rail Transit and Bus Rapid Transit [26]. Jakimavicius and Burinskiene indicated problematic transportation zones in Vilnius city according to time-based accessibility [64].

3. Research Methods

The presented research focused on the evaluation of urban transport and performance. The scope of research consists of three stages: selection, assessment, and classification (Figure 3). The TOPSIS technique selects an alternative that should simultaneously have the closest distance to the positive ideal solution and the farthest distance from the negative ideal solution. The test procedure consists of several successive steps: (1) selection of criteria and objects; (2) construction of the normalized decision matrix; (3) calculation of criterion weights based on the entropy method; (4) computation the weighted normalized decision matrix; (5) determination the positive ideal solution and the negative ideal solution; (6) calculation the separations of an alternative from the positive ideal solution and the negative ideal solution; (7) computation the ranking index; (8) linear ordering of smart cities using TOPSIS method; and (9) conclusions and finding the recommendations.

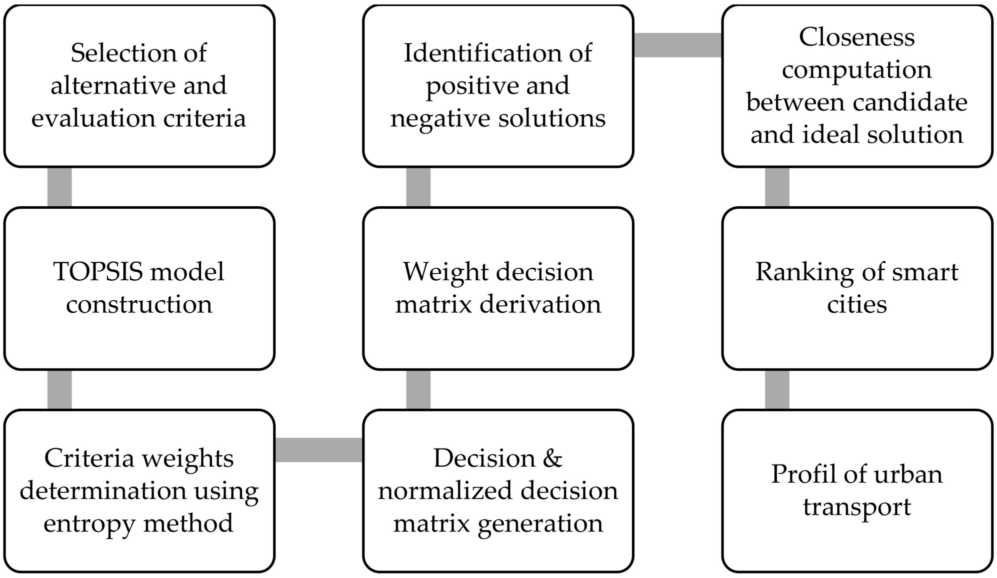

Figure 3. The research design. Source: author's work.

According to the review, the TOPSIS technique was used in this work, one of the most commonly applied to solve decision problems in field of urban transport. On the basis of the decision theory, the first method of linear ordering using the ideal solution and the negative ideal solution was proposed by C.L. Hwang and K. Yoon in 1981 under the name TOPSIS. TOPSIS takes the distance to the ideal solution and to the negative ideal solution with respect to each alternative, and chooses the nearness and farthest from the negative ideal solution. The test steps using the classic TOPSIS procedure can be concluded as follows [65]:

Stage 1. The multiple attributes were selected in accordance with substantive and statistical considerations. Then, the attributes were divided into stimulants (S) and destimulants (D).

Stage 2. The decision matrix X was established for the ranking. The structure of matrix can be expressed as follows:

$$X = [x_{ij}] = \begin{bmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{m1} & \cdots & x_{mn} \end{bmatrix} \quad (1)$$

where x_{ij} represents the value of the j-th criterion ($j = 1, 2, \ldots, n$) for the i-th alternative (city, $i = 1, 2, \ldots, m$) and $x_{ij} \in$ R.

Stage 3. The value of attributes was normalized in order to obtain their comparability in accordance with the formula:

$$r_{ij} = \begin{cases} \frac{x_{ij}}{\sum_{j=1}^{n} x_{ij}}, \text{ gdy } j \in \text{ stymulant} \\ 1 - \frac{x_{ij}}{\sum_{j=1}^{n} x_{ij}}, \text{ gdy } j \in \text{ destymulant} \end{cases} \quad (2)$$

Stage 4. The normalized (vector-based) decision matrix R was constructed:

$$R = [r_{ij}] = \begin{bmatrix} r_{11} & \cdots & r_{1n} \\ \vdots & \ddots & \vdots \\ r_{m1} & \cdots & r_{mn} \end{bmatrix} \quad (3)$$

where r_{ij} means the normalized value of the j-th criterion ($j = 1, 2, \ldots, n$) for the i-th alternatives (cities, $i = 1, 2, \ldots, m$).

Stage 5. The criterion weight vector w_j for attribute was determined based on the entropy method [66]. According to Information theory, entropy is a measure of uncertainty. The entropy weight method is an objective weighting method. The assessment matrix is constructed and standardized according to the variation degree of each attribute. The entropy weight and the entropy weight of each attribute are computed. The quotient weight of each attribute is used to weight all the attributes, so as to obtain a more objective assessment result. The steps of entropy weight:

$$E = (e_1, e_2, \ldots e_n), \quad (4)$$

where E means an entropy vector,

$$e_n = \frac{-1}{\ln m} \sum_{i=1}^{m} z_{ij} \ln z_{ij} \quad (5)$$

when:

$$z_{ij} = 0, z_{ij} \ln z_{ij} = 0 \quad (6)$$

z_{ij} represents the proportion of attribute values of the i-th alternative method under j-th index.

$$w = (w_1, w_2, \ldots w_n), \quad (7)$$

$$\sum_{j=1}^{n} w_j = 1, \; w_j \in [0, 1], \quad (8)$$

where w_j means the criterion weight.

The weights were computed according to the following formula:

$$w_j = \frac{d_j}{\sum_{j=1}^{n} d_j} \quad (9)$$

$$d_j = 1 - e_j \tag{10}$$

The entropy weight method is based on the Shannon entropy, developed by Claude Shannon [67]. It is a concept which is proposed as a measure of uncertainty in information, formulated in terms of probability theory. The entropy measures the intensities of criteria in order to represent the average information transmitted for decision making.

Stage 6. The weighted normalized decision matrix was calculated by multiplying the decision matrix by its associated weights. The weighted normalized value v_{ij} is calculated as:

$$v_{ij} = r_{ij} \cdot w_j \tag{11}$$

where w_j represents the weight of the j-th criterion.

Stage 7. The weighted normalized decision matrix V was calculated based on the weight of each attribute:

$$V = [v_{ij}] = \begin{bmatrix} v_{11} & \cdots & v_{1n} \\ \vdots & \ddots & \vdots \\ v_{m1} & \cdots & v_{mn} \end{bmatrix} \tag{12}$$

where v_{ij} means the weighted and normalized value of the j-th criterion ($j = 1, 2, \ldots, n$) for the i-th alternatives (cities, $i = 1, 2, \ldots, m$).

Stage 8. The positive ideal solution (A^+) and negative-ideal solution (A^-) were established [68]:

$$A^+ = (v_1^+, v_2^+, \ldots, v_m^+) \tag{13}$$

$$A^- = (v_1^-, v_2^-, \ldots, v_m^-) \tag{14}$$

$$v_m^+ = \left\{ \left(\begin{matrix} max \\ i \end{matrix} \; v_{ij} | j \in S \right), \left(\begin{matrix} min \\ i \end{matrix} \; v_{ij} | j \in D \right) | i = 1, 2, \ldots, n \right\} \tag{15}$$

$$v_m^- = \left\{ \left(\begin{matrix} min \\ i \end{matrix} \; v_{ij} | j \in S \right), \left(\begin{matrix} max \\ i \end{matrix} \; v_{ij} | j \in D \right) | i = 1, 2, \ldots, n \right\} \tag{16}$$

where $S = \{j = 1, 2, \ldots, m | \; j \; represent \; the \; bigger - the \; better \; attribute\}$; $D = \{j = 1, 2, \ldots, m | \; j \; represent \; the \; smaller - the \; better \; attribute\}$.

Stage 9. The separation measures were calculated, using the n-dimensional Euclidean distance. The separation of each alternative from the positive ideal solution (d_i^+) was computed:

$$d_i^+ = \sqrt{\sum_{j=1}^{m} \left(v_{ij} - v_j^+\right)^2} \tag{17}$$

Similarly, the separation of each alternative from the negative ideal solution (d_i^-) was calculated:

$$d_i^- = \sqrt{\sum_{j=1}^{m} \left(v_{ij} - v_j^-\right)^2} \tag{18}$$

where $i = 1, 2, \ldots, m$.

Stage 10. The relative closeness coefficient (RC_i) was computed whose value is always between 0 and 1. The relative closeness coefficient of the alternative can be expressed as:

$$RC_i = \frac{d_i^-}{d_i^+ + d_i^-} \tag{19}$$

where $0 \leq RC_i \leq 1, i = 1, 2, \ldots, m$.

Stage 11. The ranking of smart cities was prepared.

Stanković et al. provided the ranking of Central and Eastern European cities in context of social, economic, and environmental aspects of urban life based on combining the AHP and TOPSIS [69]. Porro et al. designed a framework oriented to public managers based on the assessment of criteria and sub-criteria the strategic location decision made by energy enterprises of European cities using AHP and TOPSIS [70].

4. Research Materials

ISO standards can be used for assessing urban transport and other dimensions of smart cities. For example, the ISO 37122 standard obtains the following indicators city streets and thoroughfares covered by real-time online traffic alerts and information, users of sharing economy transportation, low-emission vehicles registered in the city, bicycles available through bicycle sharing services, public transport lines equipped with a real-time ICT-based system, city public transport network covered by a unified payment system, public parking spaces equipped with e-payment systems, public parking spaces equipped with real-time ICT-based available system, traffic lights that are smart, and city area mapped by real-time interactive street maps [71]. Moreover, the ISO 37123 standard includes only the one indicator related to transport: evacuation routes available [72].

The starting point for the multi-criteria analysis of urban transport in this study was the indicators proposed in the ISO 37120:2014 standard [73]. The ISO 37120:2014 standard involves 46 core and 54 supporting indicators in seventeen thematic groups [74,75]. The criteria were selected from ISO 37120:2014, namely [76]:

X_1—high-capacity public transport system;
X_2—light passenger public transport system;
X_3—annual number of public transport trips per capita;
X_4—number of personal automobiles per capita;
X_5—length of bicycle paths and lanes;
X_6—transport fatalities;
X_7—commercial air connectivity.

There are four basic (X_1, X_2, X_3, X_4) and three additional indicators (X_5, X_6, X_7).

Table 3 provides a list of the general overview of the analysed cities. The urban profile involves the following characteristics, such as country, certification year, city population, city land area, population density, and city product per capita. Ahmedabad (India) is the city with the largest population (6,374,470). Guadalajara (Mexico) is the city with the largest area (2734.11 km^2). Whereas, Makati (Philippines) is the city with the highest population density (19,336.22).

Table 3. The selected cities profile.

Cities	Country	Certification Year	Population	City Land Area (km^2)	Population Density	City Product per Capita (USD)
Amsterdam	The Netherlands	2014	834,713	164.66	5065.00	71,627.00
Eindhoven	The Netherlands	2016	224,788	88.84	2530.26	97,122.00
Heerlen	The Netherlands	2016	87,406	45.53	1944	-

Table 3. *Cont.*

Cities	Country	Certification Year	Population	City Land Area (km^2)	Population Density	City Product per Capita (USD)
Rotterdam	The Netherlands	2014	618,357	208.88	2959	54,647.00
Hague	The Netherlands	2017	519,988	98.13	5298.97	45,933.67
Zwolle	The Netherlands	2017	124,896	119.30	1046.00	42,988.80
Oslo	Norway	2016	658,390	426.38	1544.14	95,628.00
Koprivnica	Croatia	2016	30,872	90.94	339.05	-
Zagreb	Croatia	2016	790,017	641.32	1232.48	20,181.20
Gdynia	Poland	2017	247,478	135	1831	-
Kielce	Poland	2017	197,704	110	1797.31	-
Barcelona	Spain	2014	1,611,822	102.16	15,777.43	-
Valencia	Spain	2015	787,266	137.48	5849.19	24,288.33
Porto	Portugal	2016	214,329	41.42	5180.50	863.75
Sintra	Portugal	2017	382,521	319.23	1198.30	20,801.29
Boston	USA	2014	672,840	125.00	5383.00	177,079.00
Doral	USA	2016	51,382	40.06	1281.02	76,066.18
Los Angeles	USA	2015	3,884,340	1301.96	2983.46	-
Portland	USA	2017	639,863	345.76	4792.6	-
San Diego	USA	2016	1,381,083	842.23	1639.79	62,295.00
Cambridge	Canada	2016	134,900	112.8	1195.92	-
Oakville	Canada	2016	194,000	138.89	1395.6	-
Saint-Augustin-de-Desmaures	Canada	2016	19,369	85.84	225.64	119,889.10
Shawinigan	Canada	2015	49,042	737	66.54	-
Surrey	Canada	2016	526,293	316	1481.01	-
Toronto	Canada	2015	2,808,503	634.00	4430.00	50,325.00
Vaughan	Canada	2015	306,233	273,56	1119.4	-
Guadalajara	Mexico	2014	4,664,559	**2734.11**	5316.35	16,263
Leon	Mexico	2015	1,514,077	1200	575.83	-
Piedras Negras	Mexico	2018	163,595	70.87	2308.38	8829.54
Torreon	Mexico	2016	679,288	305.23	2225.50	11,352.00
Buenos Aires	Argentina	2014	2,890,151	203.00	14,450.80	27,720.00
Greater Melbourne	Australia	2015	4,440,328	9990.5	444.5	44,481.53
Melbourne	Australia	2014	122,207	37.70	3088.78	587.14
Tbilisi	Georgia	2017	1,113,000	502.00	2217.13	55,343.19
Amman	Jordan	2014	2,584,600	680.00	3800.88	2705.81
Dubai	United Arab Emirates	2014	2,327,350	4114	565.71	-
Ahmedabad	India	2017	**6,374,470**	466	13,679.12	-

Table 3. *Cont.*

Cities	Country	Certification Year	Population	City Land Area (km^2)	Population Density	City Product per Capita (USD)
Pune	India	2016	5,574,000	479	6522.88	-
Makati	Philippines	2014	529,039	27.36	**19,336.22**	-
Makkah	Saudi Arabia	2014	1,919,909	483.25	3972.89	-
Tainan city	Taiwan	2017	1,886,033	2191.65	861	-
Taipei	Taiwan	2015	2,695,704	271.8	9918	-
Cape Town	South Africa	2016	4,004,793	2456	1630	5000.75

Legend: the bold type means the highest value of numbers. Source: authors' elaboration based on [77].

5. Research Results and Discussion

The research began with computing the basic statistics for urban transport indicators by measuring the position (arithmetic mean) and variability (standard deviation, variation coefficient). The most diverse indicator is the share of the transport fatalities (397.96%), while the least - the number of personal automobiles per capita (46.07%). Table 4 presents information on the general statistics of each indicator.

Table 4. Basic statistics of urban transport indicators.

	Units	Indicator Direction	$\bar{x}$	S_X	V	Min Value	City	Max Value	City
X_1	kilometres/100,000 persons	+	15.73	32.99	214.63	0.00	KP	186.98	PR
X_2	kilometres/100,000 persons	+	141.24	137.05	97.03	0.59	PU	670.90	KL
X_3	capita/year	+	220.22	362.94	164.81	0.01	KP	2097.25	MA
X_4	cars/capita	−	0.43	0.20	46.07	0.01	AH	0.92	SA
X_5	kilometres/100,000 persons	+	55.20	66.48	120.44	0.00	PN	226.74	KP
X_6	100,000 persons/year	−	11.07	44.04	397.96	0.00	KP	293.26	TB
X_7	number/year	+	142,216.18	153,963.81	108.26	0.00	SI	672,092.00	RT

Legend: a plus sign "+" means stimulant; a minus sign "−" means destimulant; $\bar{x}$—the arithmetic mean; S_X—the standard deviation, V—the variation coefficient. Source: elaborated by the authors based on [77].

In the next step, the decision matrix (X) was developed. Then, the normalized decision matrix (R) was developed based on a normalized vector (r). The results of calculated the normalized decision matrix are summarized in Appendix C.

Based on the entropy method, the entropy vector (e) and the criterion weight vector (w) were determined. Table 5 shows the weights of the evaluation criteria. The most important criterion was the transport fatalities (X_6, $w = 0.379902$), whereas the least important was the light passenger public transport system (X_2, $w = 0.010853$).

Table 5. Weights of the evaluation criteria.

	X_1	X_2	X_3	X_4	X_5	X_6	X_7
e	0.710865191	0.977335	0.871071	0.283841	0.953941	0.206623	0.90795
d	0.289134809	0.022665	0.128929	0.716159	0.046059	0.793377	0.09205
w	0.138449738	0.010853	0.061737	0.342927	0.022055	0.379902	0.044077

Source: authors' work.

Weight factors (w) were determined and the weighted normalized decision matrix (V) was developed. Appendix D presents the weighted normalized decision matrix.

The results of the calculated relative closeness coefficient (RC) and the ranking of smart cities compared to the basic level of urban transport are summarized in Table 6. Likewise, the positive distance (d^+) and the negative distance (d^-) are presented in this table. The values of the relative closeness coefficient range from 0.03504 to 0.921402.

Table 6. The ranking of smart cities.

Cities	d^+	d^-	RC	Rank
AM	0.03771132	0.227982	0.858064	8
EN	0.041789565	0.22644	0.844202	33
HE	0.039260635	0.227195	0.852656	15
RT	0.037956085	0.227862	0.857211	10
HG	0.040183827	0.227855	0.850082	19
ZW	0.032519191	0.227655	0.87501	4
OS	0.037228098	0.228552	0.859929	7
KP	0.041336763	0.22903	0.847109	26
ZA	0.040102699	0.227068	0.849899	20
GD	0.040638131	0.228612	0.849069	21
KL	0.039219893	0.226607	0.852461	16
BR	0.037795202	0.227934	0.857768	9
VA	0.039210925	0.227143	0.852786	14
PO	0.036512894	0.227688	0.861799	5
SI	0.041064964	0.227233	0.846943	27
BO	0.038025373	0.225864	0.855904	13
DO	0.041195388	0.227512	0.84669	29
LA	0.041110833	0.227337	0.846857	28
PR	0.019341474	0.226738	0.921402	1
SD	0.041458724	0.222032	0.842656	39
CA	0.04244001	0.22886	0.843568	36
OA	0.040695163	0.226558	0.847728	23
SA	0.043953375	0.228819	0.838864	42
SH	0.042387332	0.227286	0.84282	38
SU	0.041357781	0.226798	0.84577	32
TO	0.039407456	0.227604	0.852413	17
VU	0.040927315	0.22764	0.847609	24
GU	0.0419105	0.219509	0.839681	41
LE	0.040524038	0.227335	0.848711	22
PN	0.04109841	0.226729	0.846549	30
TR	0.040854204	0.226699	0.847305	25
BA	0.037546527	0.223783	0.856325	12

Table 6. *Cont.*

Cities	d^+	d^-	RC	Rank
GM	0.036768226	0.226922	0.860563	6
ME	0.022920851	0.22857	0.90886	2
TB	0.232311096	0.008436	0.03504	44
AN	0.041374464	0.223382	0.843727	35
DU	0.041297839	0.223	0.843745	34
AH	0.040843682	0.225274	0.84652	31
PU	0.041450101	0.223151	0.843349	37
MA	0.038340849	0.229027	0.856599	11
MK	0.052000828	0.197109	0.791253	43
TC	0.028670531	0.222266	0.885746	3
TA	0.03950262	0.226592	0.851546	18
CT	0.040460386	0.215567	0.841968	40

Source: authors' work.

The relative closeness coefficient (RC) was defined for each smart city. As a result, Portland (PR) was found to be the most desirable city among these alternatives, overtaking its nearest competitor, Melbourne (ME). Makkah (MK) ranked forty-three, leaving Tbilisi (TB) last.

The sensitivity analysis allowed the identification of the criteria that are particularly sensitive to weight changes, and it enabled the stability of TOPSIS rating to be examined by introducing changes to the criteria weighs. The sensitivity analysis enabled the identification of the criteria that have the greatest impact on the difference in the smart cities ranking, in terms of the proposed ranking.

The conducted analysis was accompanied by the sensitivity analysis of the final ranking to the variation of the weights of individual criteria. Relative weights of some criteria are increased and some of them are decreased according to equation [78]:

$$w_k^{new} = w_k^{old} \pm \alpha w_k^{old} \tag{20}$$

where α is the percentage change of w_k^{old};

$$\sum_{k=1}^{n} w_k^{new} = 1. \tag{21}$$

Minor changes in the criteria weights have little effect on original ranking of the forty-four cities. The results of the sensitivity analysis confirm that PR, ME, and TC are the best among cities. In Table 7, we observe a few changes in the ranking order if the criteria weights were change enormously. In addition, AM has the highest position in the maximum number of scenarios expect in scenario 5 and 7. In these two cases, a great change in priorities of criteria is observed with a big change in ranking. The ranking remains consistent unless some drastic changes are made to the weights of the criteria set. Otherwise, the sensitivity analysis shows solidity in the ranking order.

In order to validate the efficiency of the proposed TOPSIS, a comparative analysis with several approaches based on the same example can be carried out. Some of them are DEA and AHP. The calculation stages are not included here since this section is dedicated for comparison of the final rankings. Table 8 shows that the ranking order is the same, more or less, as the order due to the projected TOPSIS. The ranking order in DEA is not the same as the original study. According to this technique, ZW has an advantage over ME and OS over GM. The ranking order produced by AHP is similar to the original ranking order in this study. Thus, from the above two cases, it can be concluded that the results are harmonious with each other and they agree moderately with the results of the original preference order. The sensitivity analysis confirmed the high stability of this ranking, especially in the leading positions.

Table 7. The rank of the cities in various scenarios.

Cities	Original Ranking	Scenario 1 Ranking	Scenario 2 Ranking	Scenario 3 Ranking	Scenario 4 Ranking	Scenario 5 Ranking	Scenario 6 Ranking	Scenario 7 Ranking
AM	8	9	8	8	8	7	8	9
EN	33	33	36	33	33	33	33	34
HE	15	15	10	15	15	15	15	15
RT	10	10	15	10	10	11	10	10
HG	19	19	20	19	19	19	19	18
ZW	4	2	4	4	4	3	4	5
OS	7	6	7	9	7	8	7	7
KP	26	26	26	27	26	26	26	26
ZA	20	20	19	20	21	20	20	20
GD	21	21	21	21	20	21	21	21
KL	16	16	16	16	14	18	16	16
BR	9	8	9	7	9	9	9	8
VA	14	14	13	14	16	14	13	14
PO	5	5	5	5	5	6	5	4
SI	27	27	27	28	29	27	27	27
BO	13	13	14	13	13	13	14	13
DO	29	29	29	29	28	29	29	29
LA	28	28	28	27	28	28	28	28
PR	1	1	1	1	1	2	1	2
SD	39	36	39	39	36	39	39	39
CA	36	39	33	36	39	36	36	36
OA	23	23	23	23	23	23	23	23
SA	42	42	42	42	40	41	42	43
SH	38	38	38	38	38	38	38	38
SU	32	32	32	32	32	31	32	32
TO	17	17	18	17	17	17	17	17
VU	24	24	23	24	24	22	24	24
GU	41	41	41	41	41	42	41	40
LE	22	22	22	22	22	24	22	22
PN	30	30	30	30	30	32	30	31
TR	25	25	25	25	25	25	25	25
BA	12	12	12	12	12	12	12	11
GM	6	7	6	6	6	5	6	6
ME	2	4	2	3	2	1	2	1
TB	44	44	44	44	44	43	44	44

Table 7. *Cont.*

Cities	Original Ranking	Scenario 1 Ranking	Scenario 2 Ranking	Scenario 3 Ranking	Scenario 4 Ranking	Scenario 5 Ranking	Scenario 6 Ranking	Scenario 7 Ranking
AN	35	35	35	35	37	34	35	35
DU	34	37	34	31	34	35	34	33
AH	31	31	31	34	31	31	31	30
PU	37	34	37	37	35	37	37	37
MA	11	11	11	11	11	10	11	12
MK	43	43	43	43	43	44	43	42
TC	3	3	3	2	3	4	3	3
TA	18	18	17	18	18	16	18	19
CT	40	40	40	40	42	40	40	41

Source: author's work.

Table 8. Comparison with other models.

MCDM Techniques	Ranking Order
DEA	PR > TC > ZW > ME > PO > OS > GM > AM > BR > RT > MA > BA > BO > VA > HE > KL > TO > TA > HG > ZA > GD > LE > OA > VU > TR > KP > SI > LA > DO > PN > AH > SU > EN > DU > AN > CA > PU > SH > SD > CT > GU > SA > MK > TB
AHP	PR > TC > ME > ZW > PO > GM > OS > AM > BR > RT > MA > BA > BO > VA > HE > KL > TO > TA > HG > ZA > GD > LE > OA > VU > TR > KP > SI > LA > DO > PN > AH > SU > EN > DU > AN > CA > PU > SH > SD > CT > GU > SA > MK > TB
The proposed TOPSIS	PR > TC > ME > ZW > PO > GM > OS > AM > BR > RT > MA > BA > BO > VA > HE > KL > TO > TA > HG > ZA > GD > LE > OA > VU > TR > KP > SI > LA > DO > PN > AH > SU > EN > DU > AN > CA > PU > SH > SD > CT > GU > SA > MK > TB

Source: author's work.

Limitations and Further Study Works

The selected criteria for the evaluation of urban transport could help evaluate other cities. Therefore, there is an increasing number of scientists and practitioners to find solutions as to how, not only, to evaluate the urban transport, but also, to find prospects for their development. TOPSIS is modellable by using simple linear algebra operations. This technique considers a large number of criteria and alternatives. Analysis of all alternative are conducted after normalization, making each comparable.

The proposed approach is, however, not without limitations. This study uses available and measurable indicators while omitting those that are difficult to obtain and evaluate. Though, the analysis should be multidimensional and comprehensive. Therefore, more indicators should be considered and selected in future research. Furthermore, TOPSIS is a sensitive technique because of its method of normalization and weighing the criteria.

The results of this investigation provide theoretical support for the municipal government to formulate efficient transport policies. The paper has important value for urban study researchers and city governance practitioners, with regards to future-oriented urban transport projects concerning products with low emission of polluting gases, improvement of public transport, sustainable mobility, the use of a sharing economy, and technologies to reduce the time spent on traffic.

The paper contributes to the knowledge of city governance and managers of new business models, as well as to contemporary considerations on the competitiveness of the urban transport systems. The research findings may prove interesting primarily for city mayors and heads of urban transportation agencies and companies. Future research could be focussed on additional data and using other techniques of decision making, e.g., DEA, and AHP. There are also plans to use the TOPSIS procedure with other algorithms of normalization and criteria weighting.

6. Conclusions

In this paper, ideal solution-based multi-criteria decision-making techniques were applied for the assessment of urban transport. By using the entropy weight method and TOPSIS technique, the ranking of smart cities in terms of urban transport was obtained. Seven criteria in field of transportation were selected to build the evaluation index system.

Based on theoretical and empirical studies, the author concluded several findings. Overall, the urban transport is an important research direction, as confirmed by the growing number of publications. MCDM techniques are one of the important tools in solving decision-making problems in the field of urban transport, especially transport efficiency, sustainability performance, environmental efficiency, and low-carbon ecological city evaluation. AHP, TOPSIS, and DEA are the most popular MCDM techniques in the field of urban transport. Transport fatalities were found to be the most important criterion, followed by number of personal automobiles per capita. The ranking of smart cities in terms of urban transport was obtained based on the multi-criteria analysis. Portland was found to be the best location for transport enterprises and projects; Tbilisi was ranked last. The sensitivity analysis confirmed the high stability of the prepared rankings, and additionally, the sensitivity analysis showed solidity in the ranking order.

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Abbreviations

AM—Amsterdam
HG—Hague
ZA—Zagreb
VA—Valencia
DO—Doral
CA—Cambridge
SU—Surrey
GU—Guadalajara
BA—Bueno Aires
AN—Amman
AH—Ahmedabad
CT—Cape Town
EN—Eindhoven
ZW—Zwolle
GD—Gdynia
PO—Porto
LA—Los Angeles
SA—Saint-Augustin-de-Desmaures
PN—Piedras Negras
GM—Greater Melbourne
ME—Melbourne
TC—Tainan City
HE—Heerlen
OS—Oslo
KL—Kielce
SI—Sintra
PR—Portland
OA—Oakville
TO—Toronto
LE—Leon
TB—Tbilisi
MA—Makati
TA—Taipei
RT—Rotterdam
KP—Koprivnica
BR—Barcelona
BO—Boston
SD—San Diego
SH—Shawinigan
VU—Vaughan
TR—Torreon
PU—Pune
DU—Dubai
MK—Makkah

Appendix A

Table A1. The publications on the topic of the urban transport between 1991 and 2020.

	Elsevier	Web of Science	Scopus	Springer
1991	68	11	31	24
1992	56	11	30	26
1993	62	18	30	37
1994	82	13	29	22
1995	103	20	88	35
1996	96	34	59	52
1997	80	26	68	32
1998	59	38	93	63
1999	36	27	85	36
2000	52	59	96	43
2001	55	30	105	32
2002	57	37	128	57
2003	75	48	169	58
2004	88	40	191	53
2005	72	57	155	100
2006	91	54	195	50
2007	112	71	210	91
2008	140	89	285	96
2009	100	88	285	79
2010	127	108	347	98
2011	185	113	428	118
2012	238	133	451	156
2013	298	167	551	210
2014	344	150	532	189
2015	279	152	509	225
2016	512	284	568	290
2017	547	270	669	339
2018	502	279	720	366
2019	562	304	866	492
2020	794	294	1023	553
Total	5872	3025	8996	4022

Source: author's work.

Appendix B

Table A2. The publications with different MCDM techniques in the field urban transport.

	Elsevier	Scopus	Web of Science	Springer	Total
AHP	46	72	42	139	299
DEA	36	0	15	95	146
TOPSIS	11	19	6	53	89
ELECTRE	6	2	1	37	46
PROMETHEE	6	5	2	29	42
VIKOR	3	4	1	24	32
MACBETH	0	1	0	20	21
DEMATEL	2	4	2	12	20
REMBRANDT	0	0	0	12	12
WASPAS	1	0	0	2	3
MULTIMOORA	0	0	0	2	2
Total	111	107	69	425	712

Source: author's work.

Appendix C

Table A3. Normalized decision matrix.

Cities	X_1	X_2	X_3	X_4	X_5	X_6	X_7
AM	0.021319692	0.004226	0.027353	0.985333	0.032151	0.99696	0.03521
EN	0.001315848	0.008383	0.01961	0.967522	0.08622	0.993551	0.004857
HE	0.017017313	0.01841	0.006696	0.974332	0.093534	0.995297	0.055997
RT	0.019811642	0.002583	0.025595	0.98219	0.043055	0.996673	0.107406
HG	0.005366885	0.003675	0.011456	0.981666	0.035914	0.996817	0.060688
ZW	0.068749353	0.000241	0.005779	0.978523	0.054351	0.995892	0.055639
OS	0.026716146	0.012583	0.041065	0.976951	0.012218	0.998747	0.039634
KP	0	0.004169	0.00000103	0.980094	0.095531	1	0.006369
ZA	0.004864202	0.032201	0.035407	0.980618	0.013331	0.994804	0.006369
GD	0.006564454	0.015742	0.024769	0.971713	0.009526	0.999178	0.006103
KL	0.017194731	0.107955	0.018291	0.974856	0.01087	0.993777	0.006309
BR	0.023493059	0.009359	0.045602	0.974856	0.002743	0.997207	0.025611
VA	0.021334477	0.009449	0.016353	0.969094	0.008886	0.995338	0.003688
PO	0.027869361	0.046522	0.065689	0.982713	0.002928	0.9962	0.0000177
SI	0.011975694	0.080804	0.004506	0.964379	0.000518	0.995708	0
BO	0.017919186	0.01263	0.041742	0.985856	0.016625	0.991353	0.029612
DO	0	0.038409	0.001313	0.97957	0.017915	0.995995	0.065842
LA	0.007274125	0.009531	0.005477	0.967522	0.007672	0.995892	0.060669
PR	0.276446324	0.017106	0.00333	0.962808	0.037089	0.98587	0.030746
SD	0.003755341	0.013874	0.00703	0.977475	0.01874	0.98168	0.013748
CA	0	0.018987	0.002188	0.963855	0.039107	1	0.03711
OA	0.011354732	0.035727	0.001614	0.967522	0.043763	0.993839	0.053272

Table A3. *Cont.*

Cities	X_1	X_2	X_3	X_4	X_5	X_6	X_7
SA	0	0.044164	0.000701	0.951807	0.058404	1	0.002872
SH	0	0.008498	0.000611	0.966475	0.084096	0.99581	0.0000246
SU	0.001774177	0.009928	0.005098	0.974332	0.04386	0.994331	0.026703
TO	0.011739137	0.021921	0.020837	0.979047	0.007803	0.996262	0.042134
VA	0.007717669	0.017914	0.001959	0.969618	0.03178	0.996652	0.051514
GU	0.00076881	0.021202	0.026317	0.97957	0.000792	0.974944	0.007231
LE	0.003119594	0.037487	0.015843	0.984285	0.002827	0.995379	0.001432
PN	0	0.033317	0.005756	0.985856	0	0.993715	0.0000571
TO	0	0.029471	0.009263	0.991619	0.000931	0.993346	0.001379
BA	0.036193208	0.021366	0.0749	0.960712	0.001866	0.986424	0.009828
GM	0.042077561	0.02902	0.008434	0.96857	0.041492	0.994619	0.018277
ME	0.152091311	0.047239	0.104152	0.962284	0.062112	0.996467	0.018277
TB	0.007126277	0.064581	0.03378	0.97538	0	0.3977	0.001568
AN	0	0.006675	0.000237	0.990571	0	0.984658	0.006345
DU	0.004760708	0.03699	0.013907	0.972237	0.002751	0.984371	0.047401
AH	0.00193681	0.001447	0.0000196	0.999476	0.000476	0.989115	0.00000528
PU	0	0.0000949	0.000132	0.989523	0.00118	0.984104	0.003298
MA	0.001626329	0.000523	0.216445	0.996857	0.0000758	0.998152	0.018892
MK	0	0.00192	0.000553	0.994238	0	0.915116	0.026709
TC	0.110235522	0.021153	0.001096	0.98219	0.008043	0.980735	0.000066
TA	0.005706936	0.029368	0.049068	0.987428	0.007837	0.993222	0.004741
CT	0.022783388	0.013156	0.0000258	0.988476	0.004845	0.964099	0.006352

Source: author's work.

Appendix D

Table A4. Weighted normalized decision matrix.

Cities	X_1	X_2	X_3	X_4	X_5	X_6	X_7
AM	0.002951706	0.0000459	0.001689	0.337897	0.000709	0.378747	0.001552
EN	0.000182179	0.000091	0.001211	0.331789	0.001902	0.377452	0.000214
HE	0.002356043	0.0002	0.000413	0.334124	0.002063	0.378115	0.002468
RT	0.002742917	0.000028	0.00158	0.336819	0.00095	0.378638	0.004734
HG	0.000743044	0.0000399	0.000707	0.336639	0.000792	0.378692	0.002675
ZW	0.00951833	0.00000262	0.000357	0.335562	0.001199	0.378341	0.002452
OS	0.003698843	0.000137	0.002535	0.335023	0.000269	0.379426	0.001747
KP	0	0.0000452	0.0000000637	0.3361	0.002107	0.379902	0.000281
ZA	0.000673447	0.000349	0.002186	0.33628	0.000294	0.377928	0.000281
GD	0.000908847	0.000171	0.001529	0.333226	0.00021	0.379589	0.000269
KL	0.002380606	0.001172	0.001129	0.334304	0.00024	0.377537	0.000278
BR	0.003252608	0.000102	0.002815	0.334304	0.0000605	0.37884	0.001129
VA	0.002953753	0.000103	0.00101	0.332328	0.000196	0.37813	0.000163

Table A4. *Cont.*

Cities	X_1	X_2	X_3	X_4	X_5	X_6	X_7
PO	0.003858506	0.000505	0.004055	0.336999	0.0000646	0.378458	0.000000782
SI	0.001658032	0.000877	0.000278	0.330711	0.0000114	0.378271	0
BO	0.002480907	0.000137	0.002577	0.338076	0.000367	0.376617	0.001305
DO	0	0.000417	0.000081	0.335921	0.000395	0.37838	0.002902
LA	0.001007101	0.000103	0.000338	0.331789	0.000169	0.378341	0.002674
PR	0.038273921	0.000186	0.000206	0.330172	0.000818	0.374533	0.001355
SD	0.000519926	0.000151	0.000434	0.335202	0.000413	0.372942	0.000606
CA	0	0.000206	0.000135	0.330532	0.000863	0.379902	0.001636
OA	0.00157206	0.000388	0.0000996	0.331789	0.000965	0.377561	0.002348
SA	0	0.000479	0.0000433	0.3264	0.001288	0.379902	0.000127
SH	0	0.0000922	0.0000377	0.33143	0.001855	0.37831	0.00000108
SU	0.000245634	0.000108	0.000315	0.334124	0.000967	0.377748	0.001177
TO	0.00162528	0.000238	0.001286	0.335741	0.000172	0.378482	0.001857
VA	0.001068509	0.000194	0.000121	0.332508	0.000701	0.37863	0.002271
GU	0.000106442	0.00023	0.001625	0.335921	0.0000175	0.370383	0.000319
LE	0.000431907	0.000407	0.000978	0.337538	0.0000624	0.378146	0.0000631
PN	0	0.000362	0.000355	0.338076	0	0.377514	0.00000251
TO	0	0.00032	0.000572	0.340052	0.0000205	0.377374	0.0000608
BA	0.00501094	0.000232	0.004624	0.329454	0.0000412	0.374744	0.000433
GM	0.005825627	0.000315	0.000521	0.332148	0.000915	0.377857	0.000806
ME	0.021057002	0.000513	0.00643	0.329993	0.00137	0.37856	0.000806
TB	0.000986631	0.000701	0.002085	0.334484	0	0.151087	0.0000691
AN	0	0.0000724	0.0000147	0.339693	0	0.374073	0.00028
DU	0.000659119	0.000401	0.000859	0.333406	0.0000607	0.373964	0.002089
AH	0.000268151	0.0000157	0.00000121	0.342747	0.0000105	0.375766	0.000000233
PU	0	0.00000103	0.00000816	0.339334	0.000026	0.373862	0.000145
MA	0.000225165	0.00000568	0.013363	0.341849	0.00000167	0.379199	0.000833
MK	0	0.0000208	0.0000342	0.340951	0	0.347654	0.001177
TC	0.015262079	0.00023	0.0000677	0.336819	0.000177	0.372583	0.00000291
TA	0.000790124	0.000319	0.003029	0.338615	0.000173	0.377327	0.000209
CT	0.003154354	0.000143	0.00000159	0.338975	0.000107	0.366263	0.00028

Source: author's work.

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