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COMPREHENSIVE METHODOLOGY FOR URBAN METRO PLANNING

Summary. This article presents a thorough methodology for the planning of new urban metro systems by incorporating multi-regional empirical data alongside city-specific correction factors. This approach facilitates a more precise estimation of the necessary line length and the number of stations required. This research presents a systematic algorithm that produces various design alternatives, taking into account factors such as population, geographical area, and transportation demand, thereby tackling the significant variability noted among current global metro systems. A notable aspect of this work is the incorporation of operational performance forecasting, which includes elements such as crime rates, emergency response times, passenger density, and renewable energy utilization. This illustrates that these indicators are influenced not solely by the physical parameters of the system but also by wider social and infrastructural contexts. The proposed methodology offers urban planners a versatile, data-informed instrument that can be utilized across various urban contexts, thereby improving initial decision-making processes that promote sustainable metro development.

1. INTRODUCTION

In recent decades, the world has witnessed rapid metro development, especially as urbanization has increased. According to a recent study on the KAMPALA-TIMES model [1], the creation of a new metro line or an entire metro system can become the main axis of the urban transport network, related to common global directions, such as introducing clean energy, promoting economic growth, and achieving common sustainability goals. This study emphasizes the potential of the electrified metro to significantly reduce pollution and CO_2 emissions while shaping the direction of a greener economy [2].

Global urbanization is advancing rapidly, and it is projected that by 2050, over 68% of the world's population will reside in urban areas [3]. This transformation is anticipated to markedly elevate the demand for transportation systems characterized by high capacity, low emissions, and resilience [4]. Modern urban networks are regarded not merely as transportation systems but also as essential instruments for attaining sustainable development objectives. Metro systems facilitate sustainable transportation by decreasing dependence on private automobiles, enhancing air quality, reducing carbon dioxide emissions, and fostering densely developed urban areas [5].

Recent research has revealed the concept of cognitive sustainability, emphasizing the impact of transportation systems on human behavior, perceptions, and decision-making processes [6]. Research in this sector indicates that well-structured metro systems reduce the cognitive burden associated with daily travel, enhance accessibility, and boost the adaptability of transport systems, ultimately leading to greater user satisfaction [7]. The concepts articulated in the contemporary literature on cognitive sustainability and cognitive mobility substantiate the argument that metropolitan planning must encompass not merely engineering and geographical attributes but also the essential considerations of human-centered mobility [8].

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Cities like Delhi [9], Xi'an [10, 11], Shanghai [12], and Doha [13] exemplify how regional authorities and planners are using metros to optimize urban transport and mobility to reduce congestion. In addition, a more sustainable urban image is being created. Some cities have already shown that the introduction of the metro improves the efficiency of public transport, shortens travel times, and reduces the number of cars on the streets [14].

In summary, the establishment or development of a metro system in many places has become a strategic investment for countries and cities, as it is directly linked to a faster pace of urbanization and an increased competitiveness of cities [15, 16]. As mentioned in a study examining Delhi [9], the staircase effect of opening new stations promotes the spatial development of the city and is directly linked to the formation of urban structures and new centers of attraction for people.

When creating and developing metro systems, it is important to integrate transport planning with urban planning. For example, the Delhi Metro [9] illustrates that the systematic emergence of stations is not only a transport project but also an engine of urban development. Newly built lines attract investment to surrounding areas; change their land use through, for example, commercial development and residential densification; and form sub-centers.

Cities facing congestion and air pollution prioritize the optimization of public transport [17, 18]. One study discussing the integration between the metro system and other modes of transport [19] emphasized that bike or scooter sharing services essentially provide a last-mile solution, while the metro itself acts as a backbone covering major routes and corridors. Such a connection increases the accessibility of the entire transport system and helps citizens optimally use the capacity of public transport [20]. However, potential conflicts have also been emphasized. For one, the metro is not very competitive with bicycles [21], but some travelers still choose to use a bicycle even when there is a fairly convenient metro station if the distances are not too great [22].

Recent research highlights that effective metro planning is closely linked to the principles of transit-oriented development. Transit-oriented development promotes the establishment of compact, mixed-use developments in proximity to metro stations, supported by infrastructure that prioritizes pedestrian access and improves multimodal connectivity. Investigations carried out in Delhi [9], Xi'an [10, 11], and Shanghai [12] reveal that areas surrounding transit-oriented development stations increase ridership, improve the quality of urban spaces, and lead to more effective land use. The global scholarly discourse highlights that transit-oriented development can mitigate urban sprawl while fostering the enduring sustainability of metropolitan investments.

A notable domain of inquiry involves the amalgamation of metro systems with micro-mobility services, such as shared bicycles and scooters. Research conducted by Sana and Safa [23] suggests that the interactions between metro and bike systems can be complementary, competitive, or hybrid relationships, based on factors such as station spacing, urban configuration, and travel distance. The effective implementation of first/last-mile solutions significantly improves metro accessibility and encourages a shift in travel behavior from private vehicles.

Furthermore, sustainability metrics are increasingly being used to evaluate metro system performance, including CO_2 reduction potential, renewable energy use, and user-perceived service quality. Recent publications also link transport sustainability with cognitive aspects, such as how travelers perceive system complexity, safety, and reliability. These findings support the need for metro planning methodologies that incorporate not only engineering and spatial indicators, but also behavioral, energy-related, and environmental dimensions.

Another important element of urban planning is the development strategy of the territories around stations and lines. Many sources (especially [12] and [24]) draw attention to the fact that new business centers, residential areas, or social infrastructure facilities are emerging in the areas around stations. Here, the principles of transit-oriented development emerge, which, if well planned, can change the face of the city by supporting higher building density, mixed-use spaces, and good pedestrian and bicycle connections with station infrastructure. Cases are also mentioned (e.g., in Xi'an, [11]) in which the successful integration between the station and the surrounding urban structure leads to a significant increase in passenger flows.

1.1. Terminology

For clarity and consistency, the following key terms are used throughout the paper:
- Metro density (km/km²) – total length of metro lines divided by the administrative area of the city (in square kilometers). This indicator expresses how intensively the metro network covers the urban territory.
- Station density (stations/km²) – total number of stations divided by the city area. This reflects the spatial accessibility of the metro system within the urban fabric.
- Line length per million inhabitants (km/million inhabitants) – total metro system length divided by the city population (in millions). This indicator is used to compare cities of different population sizes.
- Stations per million inhabitants (stations/million inhabitants) – total number of stations divided by city population (in millions). It describes the level of metro service intensity relative to population.

2. METHODS AND MATERIALS

The methodology consists of two parts. The first part is intended to determine the required length and number of stations of the metro system, taking into account parameters that describe the size of a city, such as population, passenger numbers, and city area. The operational indicators used in the second part of the methodology—crime levels, emergency response times, passenger density, and renewable energy use—were obtained from several publicly available international datasets. Crime and safety statistics were sourced from official metropolitan transport authority reports, including Transport for London (TFL), RATP (Paris), MTA (New York), BVG (Berlin), and Montreal STM annual safety reports. Additional comparative data were retrieved from the UITP "Metro World Figures" publication and the ASU Metro Data Center database. Emergency response time indicators were extracted from transport authorities' annual operational reviews or city emergency services' performance reports. Renewable energy usage indicators were collected from sustainability and environmental statements published by metro operators in Europe, America, and the Baltic region.

Several methodological limitations must be acknowledged. First, cities differ significantly in terms of how incidents and crimes are classified; what is considered a minor service disruption in one system may be reported as a formal incident in another. Second, the reporting intervals and data granularity vary across operators, which may introduce comparability constraints. Third, operational indicators such as crime or response time are influenced by local social, infrastructural, and institutional characteristics that are not directly linked to metro system parameters. Thus, the methodology of the current study aims to provide a structured initial forecast rather than a deterministic prediction, and the indicators should be interpreted as approximate values suitable for pre-planning stages. For this purpose, data are taken from literature sources such as the UITP (International Association of Public Transport) website, the official U.S. Census Bureau international database website, or the Arizona State University (ASU) database website [25–27]. The periods for which data are provided in the aforementioned sources differ slightly, but these differences are not significant and, in the authors' opinion, not essential.

The second part is designed to anticipate the future (hypothetical) operational characteristics of the metro system, as well as potential problems (please clarify where the data for the figure in Part Two are obtained).

When beginning to develop the first part of the methodology, one might assume that its principle could be straightforward—namely, to consider global practice on what kind of metro systems are typically operated in cities of different sizes. Then, based on the size of the city under consideration, one would calculate the required system length and number of stations accordingly. However, when we started to analyze how the length of metro systems and the number of stations correlate with city areas and populations, it became apparent that this task is not simple. Before beginning this analysis, initial data on metro systems—specifically, system length and number of stations—were collected (Table 1).

<div align="right">Table 1</div>

<div align="center">Initial Data on Metro Systems</div>

Europe			Baltic Region Countries			America		
City	Metro System Length (in kilometers)	Number of Stations	City	Metro System Length (in kilometers)	Number of Stations	City	Metro System Length (in kilometers)	Number of Stations
London	470	272	Copenhagen	38.2	44	New York	1,370	472
Madrid	291	289	Berlin	146	175	Mexico City	227	195
Moscow	435	250	Warsaw	29	28	Montreal	69,2	68
Paris	214	304	Helsinki	43	30	Toronto	76.9	75
Berlin	146	175	Stokholm	106	100	Washington	190	91

On a preliminary basis, the data in Fig. 1 show that, in broad terms, the dependence of metro system length on both population size and city area is quite evident and logical. A larger population corresponds to a longer metro system, and a larger city area corresponds to a longer metro system. However, when the data are examined by region (the Americas, Europe, and the Baltic region), it can be seen that the dispersion of the data displays signs of segregation. For example, the population in Baltic region cities (those that have a metro system) does not exceed 4 million, and the area does not exceed 1,000 square kilometers. Meanwhile, the population in European cities can reach up to 12 million, and the area can span up to 2,500 square kilometers. The data from metro systems in cities of the Americas do not exhibit any peculiarities (note: metro systems in the United States are not considered here).
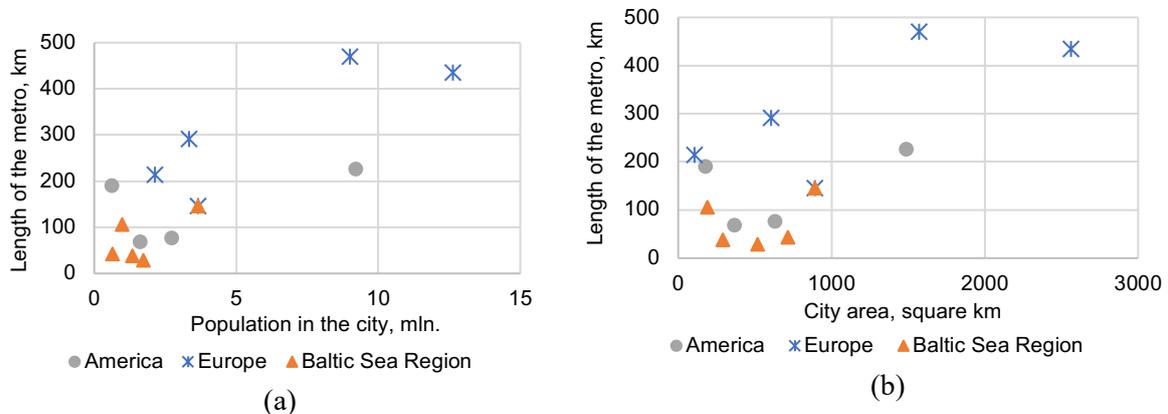

Fig. 1. Dependence of metro system length on population (a) and city area (b)

Fig. 2 shows how the number of metro stations depends on city size parameters.

The dependencies in Fig. 2—specifically, the number of metro stations in relation to both city population and city area—raise doubts as to whether it is worth searching for a direct correlation. For instance, the number of stations in European metro systems generally ranges from 250 to 300 (with the exception of Berlin, which has 175), while in Baltic region cities, the station count does not exceed 100 (again, with Berlin being an exception).

However, based on the data shown in Figs. 1 and 2, it is possible to calculate relative indicators, such as metro density (km/km²), metro system length (km) per million inhabitants, number of metro stations per unit area (stations per km²), and number of metro stations per million inhabitants.
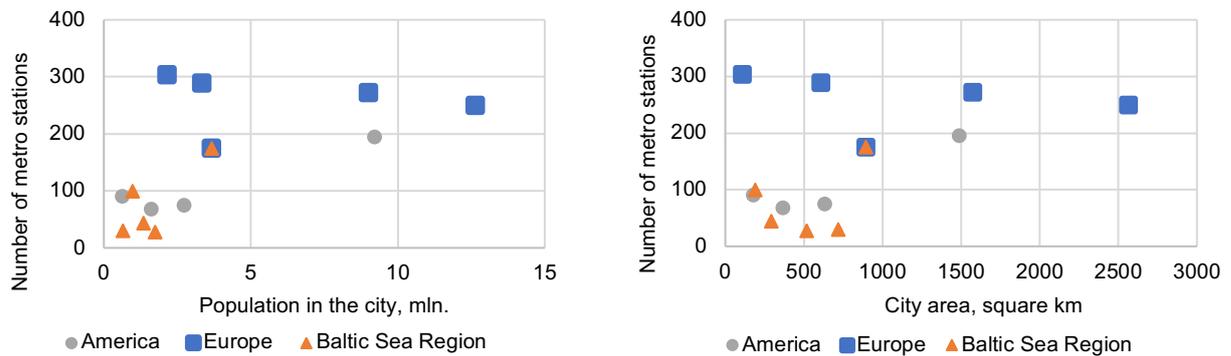
Fig. 2. Dependence of the number of metro stations on population (a) and city area (b)

A summary of the values of these indicators is presented in Table 2.

Summary of Relative Indicators for Metro Systems

Region	Metro Density (1/km)	Metro System Length (km per Million Inhabitants)	Number of Metro Stations per Unit of Area (stations per km²)	Number of Metro Stations per Million Inhabitants
America	0.533	111.30	0.268	57.97
Europe	0.630	62.76	0.768	65.31
Baltic Sea Region	0.195	51.93	0.195	49.03

After a preliminary review of the data in Table 2, some fundamental methodological questions arise: how can the relative indicators of existing metro systems be used as a reference for modeling new metro systems? Which algorithm should be applied to calculate the equivalent indicators for future systems? It is possible to base the calculations on any of the values presented in Table 2 (there are a total of 12: six pertaining to system length and six pertaining to the number of stations). Each choice would be logical in a certain sense, but each would produce a different result. Consequently, for every city where a metro system is being modeled, six variants of potential system lengths and six variants of potential station counts would be calculated (in total, six variants, not 6 × 6).

3. RESULTS

Three system length variants would be calculated proportionally according to the city area, and three would be calculated according to the population size. The same approach would be used for the calculation of the number of stations.

When analyzing the trends shown in Fig. 3, it should be kept in mind that the areas of cities in the Baltic countries (for example) are as follows: Vilnius – 401 km², Riga – 307 km², and Tallinn – 160 km². If metro density is selected based on the city's area, then, according to the data from Baltic region cities, for cities of this size, the density should be between 0.01 and 0.3 km/km². For European cities, these figures range from 0.5 to 1.5 km/km². On average, the numbers differ by a factor of about five. In pursuit of greater precision, Fig. 4 presents an analysis of the dependence of metro density (km per million inhabitants) on the population of the city.
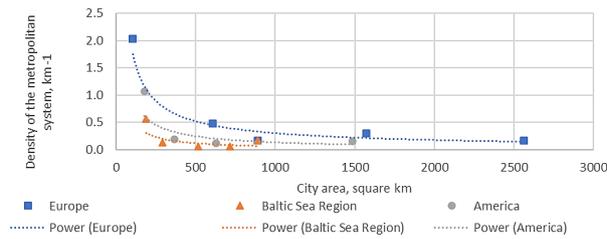
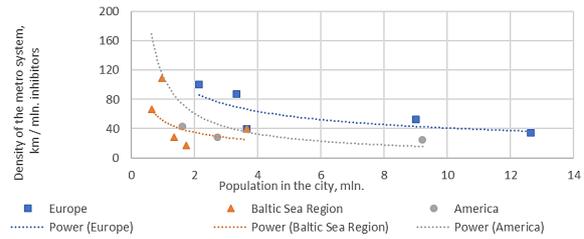Fig. 3. Dependence of metro system density on city area

Fig. 4. Dependence of metro density (km per million inhabitants) on city population

When analyzing the patterns shown in Fig. 4, we keep in mind that the populations of cities in the Baltic countries (for example) are as follows: Vilnius – 605,000 residents, Riga – 605,000 residents, and Tallinn – 461,000 residents. According to data from countries in the Baltic region, the indicator under examination is approximately 20 to 100 kilometers per million inhabitants. Compared to the findings from the analysis of Fig. 3, the data in Fig. 4 do not yield a qualitatively new outcome. In the pursuit of greater precision, the dependence of metro station density on city area is examined (Fig. 5).

Fig. 5 shows that larger European cities (with an area of more than 1,000 km²) have roughly the same metro station density as Baltic region cities, which have an area of around 500 km². However, in smaller European cities, the number of metro stations is significantly larger (in some cases, by an order of magnitude). As with the patterns observed in Figs. 3–5, one cannot rely on these findings absolutely. The dependence of the number of metro stations on the population size is shown in Fig. 6.
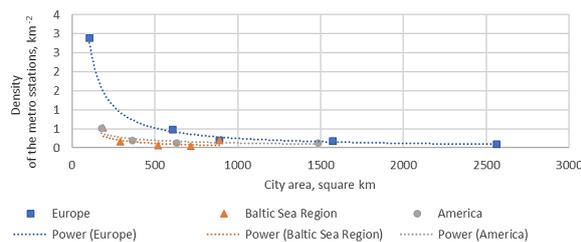

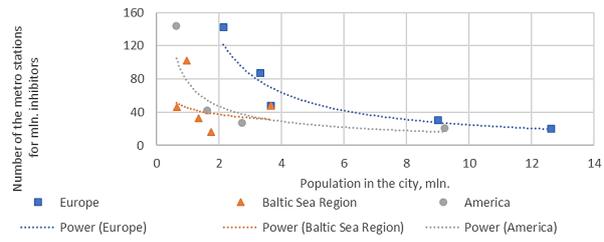Fig. 5. Dependence of metro station density on city area

Fig. 6. Dependence of the number of metro stations on population

The data in Fig. 6 show a similar trend as the data in Fig. 5, although the point of reference differs. In European cities where the population exceeds 5 million, the number of metro stations per million inhabitants is similar to that in the Baltic region cities (where the population typically does not exceed 2 million). However, if one considers European cities with a population of less than 5 million, the number of metro stations per million inhabitants is more than five times greater.

When summarizing the attempts to develop a methodology for determining metro system length and the number of stations while taking into account parameters that describe city size – such as population, passenger numbers, and city area – it becomes clear that it is not straightforward to rely on any single precedent. One cannot unequivocally rely on the examples of European, American, or Baltic cities, as different cities have implemented their metro systems based on different conceptual approaches. Although there is no obvious algorithm to derive a generalized concept, such an algorithm can be created.

Fig. 7 schematically summarizes the methodology, allowing us to trace how the initial city indicators – its area, population, and transport demand – are used to determine specific metro system parameters (total line length and number of stations).

Data from various cities show that there is no universal methodology suitable for all cases. In some countries, the metro is planned very densely (for smaller but intensively urbanized territories), while in others it is more extensive and includes suburban areas. In Europe and America, the indicators of larger cities (over 5 million inhabitants) do not depend on the same "rule" curve as medium-sized cities or

the capitals of the Baltic States. Therefore, the results based on just one region may be inaccurate. Even among cities with a similar population and area (e.g., about 1–2 million inhabitants), the values of station density or line length may differ several times. This is determined by different priorities: in one place, investments might be made in a denser network of stations in the city core, while in another, longer routes might cover the suburbs.

Since the consistent application of the "averages" of one region yields generalized results, the methodology suggests using corrective factors that reflect the goals of the city (e.g., transport sustainability policy, population density, geographical restrictions). The calculated length of the metro and the number of stations, even when carefully combining data with the experience of other cities, remain a starting point for discussions, because a real project always requires more detailed (engineering, economic, urban) justification.

In summary, the algorithm shown in Fig. 7 allows you to "transfer" the best practices and quantitative indicators of different cities, but the final solutions must be localized. Thus, the main trend is that each city, even if it has similar statistical parameters as others, forms its own vision of the metro network, depending on the specifics of the region, the needs of citizens, and strategic ambitions.

Fig. 8 shows that the number of crimes per million passengers in various metropolitan networks of cities around the world ranges from about 15 to almost 50. The highest crime rates are recorded in London, Washington, and Paris, where over 40 crimes per million passengers are recorded. Such indicators can be associated with very intensive passenger flows, complex infrastructure, and greater social diversity. Meanwhile, the indicators of cities such as Moscow, Berlin, Madrid, New York, and Montreal fall into the average category (about 25–35 crimes per million passengers), and the lowest levels are observed in Mexico City, Warsaw, Copenhagen, Helsinki, and Stockholm (about 15–25 crimes per million passengers).

Such a range of differences shows that it is difficult to assess the overall safety of the metro using statistical indicators alone because a crime might be recorded as a violation of public order in some cities and as a minor incident in others. Infrastructure solutions (e.g., Camera networks, security personnel, and station gates), the social environment, and law enforcement also play important roles. In large cities with complex transport hubs and higher passenger turnover, opportunities for crime naturally increase, but effective preventive measures can significantly reduce the overall crime rate. However, the data presented in Fig. 8 provide an initial understanding of which cities face greater challenges. It is important to note that high or low crime rates do not indicate specific causes, so it is worth examining the social and urban characteristics of each city in more depth. This analysis can help city authorities and transport planners to assess potential risks and adapt good practices from other cities to more effectively prevent crime and ensure greater public transport safety.

Fig. 9 shows that the arrival times of emergency services (e.g., ambulances, fire brigades, and security teams) to metro incidents in different cities around the world range from approximately four to eight minutes.

The lowest rate was recorded in Berlin (about four minutes), while passengers in Paris may have to wait the longest for help (about eight minutes). Intermediate cities, such as London, Washington, Moscow, New York, and Madrid, usually have a response time of five to seven minutes. These differences can be explained by several factors: firstly, the denser and better located metro infrastructure and special service points, the shorter the path to the scene of the incident. Secondly, the level of modern technologies (e.g., smart cameras and the efficient work of dispatchers) also determines how quickly an incident is recorded and a rescue crew is dispatched. Third, in larger cities (London and Paris), traffic and people flows are more complex, so it may take longer for emergency services to reach the station. However, the difference between the fastest and slowest responding cities is not substantial, but even a minute difference can be fatal in extreme situations. Such statistics reveal why some cities pay more attention to active preventive measures (e.g., patrolling stations), while others invest in comprehensive measures (e.g., a well-organized dispatch system, an efficient station network layout, and fast-reacting services). Cities where the average response time reaches six or seven minutes are advised to evaluate their current planning in detail and consider possible improvements, from installing additional service bases to installing more advanced communication systems that can shorten the waiting time for help.
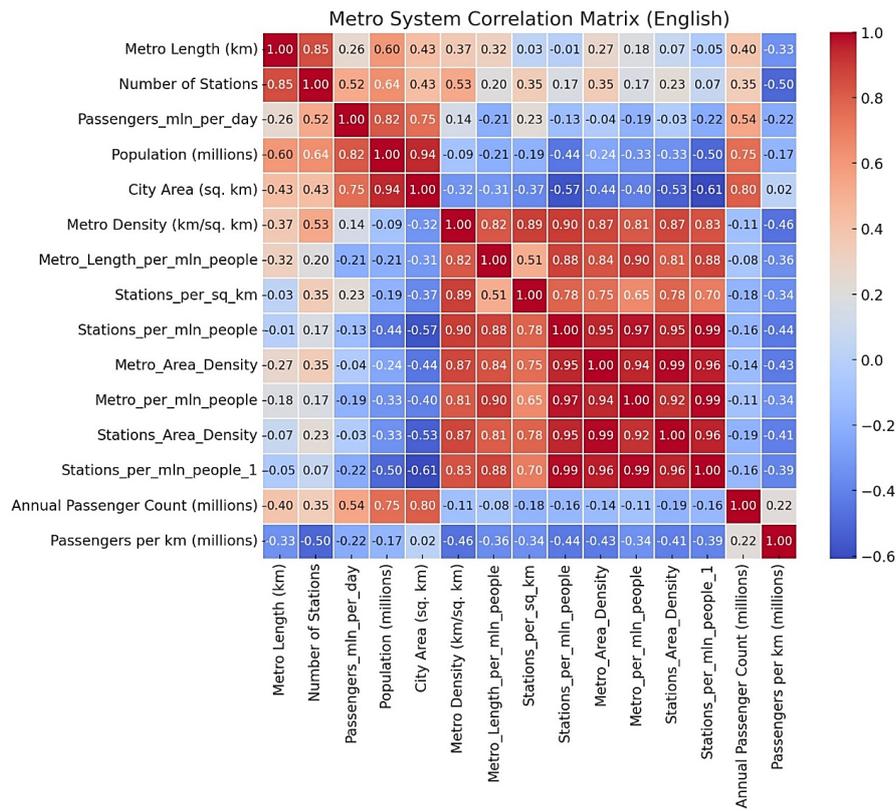
Fig. 7. Schematic algorithm for predicting the length and number of stations of a metro system
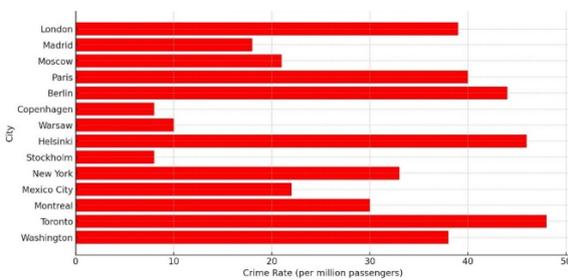

Fig. 8. Comparison of crime rates in different metropolitan areas of cities around the world
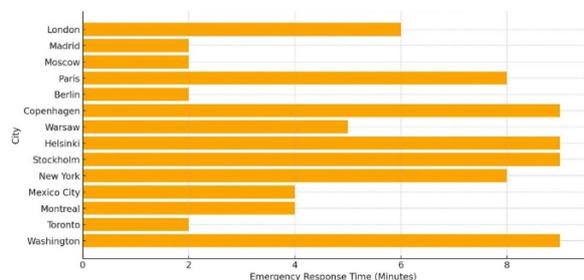

Fig. 9. Comparison of emergency response times in different metropolitan areas of cities around the world

When planning to install a metro system in a city, it is necessary to predict its impact on the environment. This impact can be indicated by indicators such as passenger density in the metro, crime, emergency responses, and the use of renewable energy. While there may be more indicators, the goal of this study is not to increase the number of indicators but to determine how the mechanisms for predicting indicators work. Therefore, the study focused only on the listed indicators. The dependence of passenger density on the length of the metro system and the number of stations is shown in Fig. 10.

The data for the dependence of passenger density on the length of the metro system and the number of stations show that the spread of values is not large, as passenger density fluctuates around 4.14 in European cities, around 4.5 in American cities, and around 5.0 in Baltic cities. It can be concluded that this indicator should be fairly predictable. A more difficult indicator to predict is the relative crime rate (measured as the number of crimes per million passengers). The dependence of the relative crime rate on the length of the metro system and the number of stations is shown in Fig. 11.
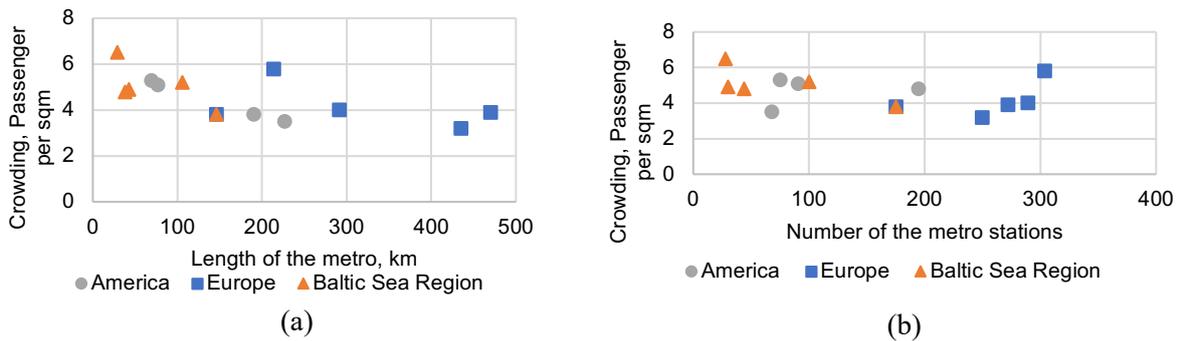
Fig. 10. Dependence of passenger density on (a) the length of the metro system and (b) the number of stations

Fig. 11 shows that the relative crime rate fluctuates around 32.0 in European cities, around 33.8 in American cities, and around 23.0 in Baltic cities. However, a more important feature, as shown in Fig. 11, is that the relative crime rate is a difficult indicator to predict. In American cities, it is almost evenly distributed from 20 to 50 (approximately), in European cities, it is distributed from 20 to 40, and in Baltic cities, it is distributed from 10 to 50. It will not be possible to see the mathematical dependence of these numbers on the length of the metro system and the number of stations here (an exception could be American cities, where there may be some correlation – the larger the system, the lower the relative crime rate). According to the data in Fig. 11, crime rates in metro stations could be determined more by other factors, such as societal culture, rather than by metro parameters (system length or number of stations).
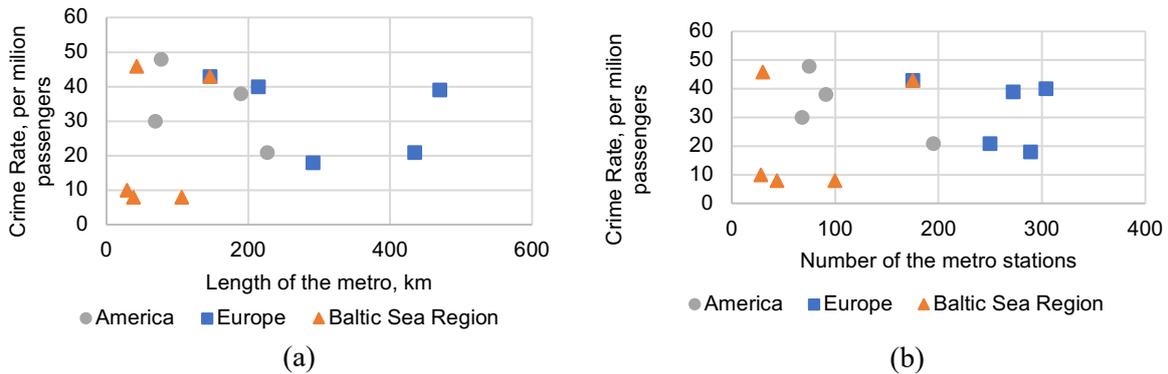

Fig. 11. Dependence of the relative number of crimes on (a) the length of the metro system and (b) the number of stations

Ambulance efficiency is defined as the time it takes an ambulance to arrive at the required metro station. The dependence of this indicator on the length of the metro system and the number of stations is shown in Fig. 12.

According to the data in Fig. 12, the ambulance efficiency varies around 4.0 minutes in European cities, 5.4 minutes in American cities, and 6.8 minutes in cities in the Baltic region. In practically all cases, the ambulance arrival time varies between two and nine minutes. A mathematical correlation could be seen in the dependence on the number of stations in the case of European cities – specifically, the more metro stations there are, the longer it takes an ambulance to arrive at them. The data in Fig. 12 reveal that the time of ambulance arrival at metro stations is determined more by the capabilities of the ground transport system than by the parameters of the metro system (system length or number of stations).

When examining a metro system from the perspective of a green course, the first step is to assess what share of energy is obtained from renewable sources. Fig. 13 shows how the percentage of renewable energy use varies according to the length of the metro system and the number of stations.
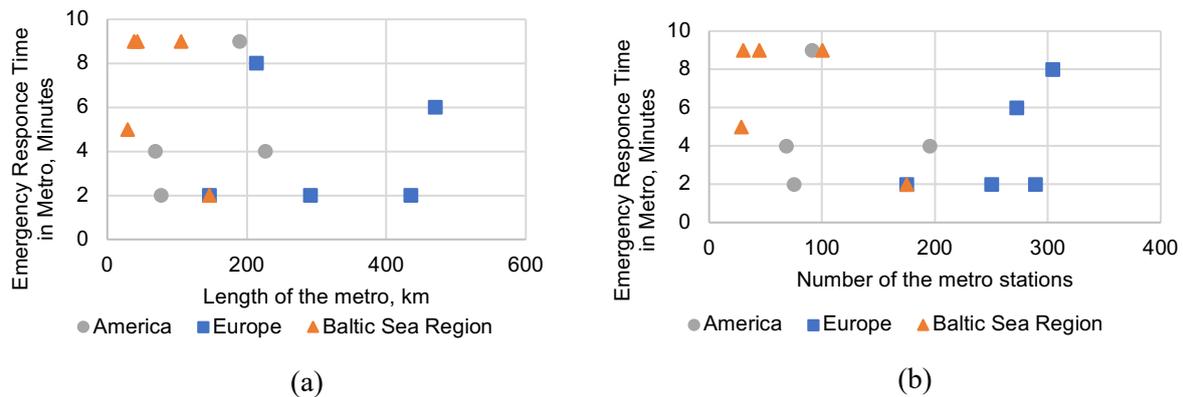
Fig. 12. Dependence of ambulance speed on (a) the length of the metro system and (b) the number of stations

The percentage of renewable energy use (according to the data in Fig. 13) varies around 51.8 in European cities, 45.8 in American cities, and 41.6 in cities in the Baltic region. This percentage is the most widely spread in European cities (33 to 62), and the most predictable in American cities (43 to 58). According to the data in Fig. 13, the percentage of renewable energy use depends not so much on the parameters of the metro system but rather on the attitudes and efforts of developers.
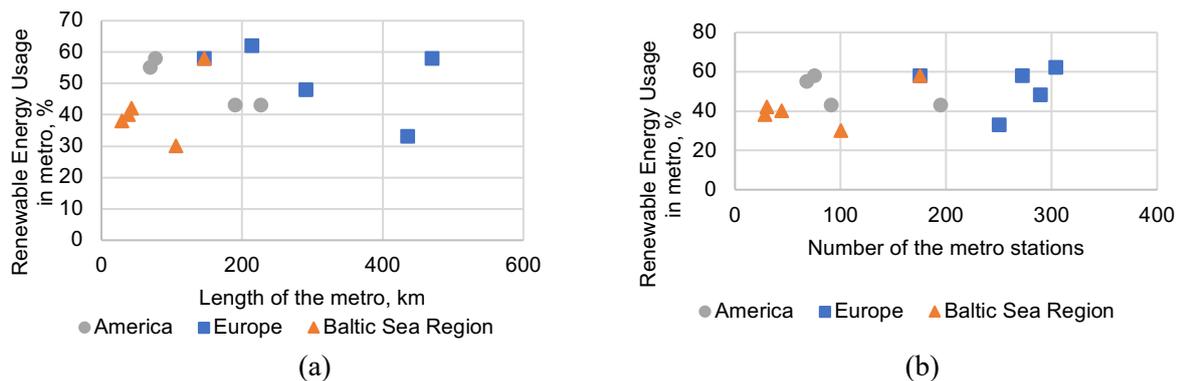

Fig. 13. Percentage of renewable energy use by (a) metro system length and (b) number of stations

4. CONCLUSIONS

This study demonstrates that operational metrics, such as crime rates, emergency response times, passenger density, and the share of renewable energy, are influenced by the intrinsic physical characteristics of metro systems as well as by broader social, institutional, and infrastructural factors. Nevertheless, it remains feasible to make preliminary assessments of these indicators, and they serve as valuable tools for evaluating the potential future performance of the system. This indicates that the establishment of new metro networks requires a holistic strategy that includes not just the physical infrastructure but also considerations such as safety, governance, environmental objectives, and the quality of service provided.

The proposed methodology will be highly beneficial for urban planners and policymakers, as it enables the generation of a diverse array of design concepts for new metro systems and facilitates the evaluation of their efficacy across various urban environments. The absence of a universal model applicable to all towns underscores the need for adaptability, particularly in adjusting parameters to accommodate the unique requirements of each city. In summary, the approach establishes a coherent and systematic structure for the initial phases of constructing metro systems, which will aid communities in making informed decisions that enhance the long-term sustainability of urban mobility.

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