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Sustainable Mobility and the Smart City: A Vision of the City of the Future: The Case Study of Cracow (Poland)

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Abstract: The vision of the smart city is inextricably linked with the concepts of intelligent transport, sustainable mobility and managerial decision making. Cities of the future not only entail the use of new technology, but also increasingly the interpenetration of technological and social aspects, with the simultaneous involvement of urban space users in the creation of such technologies. This provides an opportunity to introduce desired changes and create a more balanced space with a higher quality of life and improved energy efficiency. The article discusses the concepts of sustainable development and sustainable mobility with a particular emphasis on issues related to the smart city. The authors reviewed the various smart city solutions that have been implemented in the field of urban transport in Cracow, whose authorities have taken steps over the last few years to make the city smarter and more modern. The aim of the research was to assess the contribution made by smart city solutions to improving the attractiveness and reliability of public transport in Poland's second-largest city. The undoubted added value of this analysis is the application of the Structural Equation Modeling (SEM) method to evaluate the implemented solutions. It should be pointed out that such an analysis constitutes a new approach in this area. Until now, these models have been used to assess consumer behavior. The results showed that some of the implemented intelligent solutions increase the attractiveness of public transport in Cracow, but this does not square with users' assessment of reliability. According to users, ecological solutions have no impact on the attractiveness of public transport. Nor do conveniences such as bus lanes, giving priority to public transport vehicles at intersections, and adjusting traffic light regulation to traffic volume, have a positive impact on perceptions of public transport as a reliable means of getting around the city. The results may be of particular importance for the city's authorities and other stakeholders engaged in strategic activities and the building of a city of the future.

Keywords: smart city; smart mobility; sustainable urban mobility; sustainable transport; SUMP; strategy; Cracow; Poland; structural equation modeling—SEM

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1. Introduction

The nineteenth century belonged to the Great Powers, the twentieth century was the age of nations, but the twenty-first century will be dominated by cities [1], which in a rapidly changing world have become important sources of competitiveness [2] as well as financial and economic benefits [3]. The smart city is one of the main trends of the fourth industrial revolution [4]. As a consequence, the implementation of the concept of the smart city, taking into account the assumptions of sustainable development and transport, is an important factor in the development of Revolution 4.0. Smart City Strategies provide space for innovation and greater participation by citizens and civil society [5].

Changes in this direction are particularly desirable [6], given the problems faced by modern cities. Progressive urbanization, the availability of passenger cars, demographic and socio-economic changes [3,7,8], the degradation of central areas, urban congestion, and poverty [9] are just some of the factors that are undermining the quality of life and the natural environment. One response to the global trends and challenges connected with ongoing urbanization has been to implement international goals and actions aimed at promoting the sustainable development of cities [10].

Guidelines for shaping urban policy on sustainable development can be found in documents such as Agenda 2030 [11] and the New Urban Agenda. Their main goal is to eliminate poverty and social inequality in cities, improve the overall quality of life in urban areas, ameliorate environmental conditions in cities and prevent the occurrence of crisis situations [10]. Importantly, the New Urban Agenda prioritizes proper planning and management in cities with the aim of ensuring a high quality of life, health, safety and economic development. It promotes, among other things, sustainable urban mobility, the principle of social participation and the idea of the smart city. Researchers have identified sustainable transport as one of the factors driving the development of smart cities [12,13], and the smart city is a key concept driving sustainable urban development around the world, covering a wide range of issues related to effective, sustainable city management [14].

However, it seems that no smart city can exist without sustainable mobility, and there is no such thing as sustainable mobility without smart solutions. Bamwesigye & Hlavackova [12] believe that "the two terms have much in common with regard to their elements and results, and that their main goal is to achieve better living conditions for urban communities". The authors of the present study believe that these ideas complement each other and can be an effective tool for building the city of the future. It should be clearly emphasized that this is not a panacea for all the problems of modern cities. It is important that appropriate steps are taken, not only at the international level, but also, and above all else, at the national and local levels.

Polish cities also face increasing challenges in the area of socio-economic, ecological, functional and sustainable development [15,16]. Cracow is a particularly interesting example in this case. The second-largest city in Poland, it is regarded as a perfect location for international business [17], due to the availability of local specialists, its modern office space, scientific and research potential, cost effectiveness and high quality of life. In 2017 Cracow was ranked second in Europe and eighth in the world in terms of its attractiveness for investors [18]. Undoubtedly, it has the potential to attract new residents and entrepreneurs, and yet despite the fact that it enjoys a reputation as a positive place to live, work and relax, like most modern cities it struggles with a number of problems resulting mainly from increasing urbanization. Traffic congestion and resultant air pollution are considered to be among the most serious problems arising from urban development. Of particular concern is the city's excessive particulate emissions [7,19,20]. Cracow is one of the most polluted cities in Poland and has one of the poorest levels of air quality [21–23]. Studies of particle emissions [24] indicate that the largest source of air pollution in Cracow is transport outside households.

Moreover, the city's increasing population combined with the construction of housing estates both within the city's administrative borders and outside have given rise to the phenomenon of congestion [25]. Another problem is residential buildings in the vicinity of roads, which are exposing residents to the harmful effects of noise [26] and have reduced the value of their properties [27]. Yet another impediment to development in Cracow has been the difficulties connected with the city's transport and road network [14,28,29]. As a consequence, every attempt should be made to limit and ease traffic congestion in urban centers and highly urbanized areas [21] and the smart city concept may prove helpful in this respect.

For years, the city's authorities have been taking steps consistent with the vision and mission of its strategy aimed at developing a modern and intelligent metropolis that ensures a high quality of life built on the foundations of tradition and history, and supported by cooperation between a broad coalition of partners and involving the active participation of residents [30]. Building a smart city is one of the priorities of future development [5,31] and the changes achieved so far should be assessed in a positive light, as is also confirmed by the results of rankings comparing and evaluating smart city-related activities.

Cracow is rated one of Poland's most intelligent cities in national rankings [32,33], while in international rankings it does not differ significantly from the average scores for European cities as a whole [34,35]. Besides these rankings, numerous studies have also been conducted, the aim of which was to determine whether Cracow is a smart city as well as to evaluate the level of intelligence in Polish cities [5,14,32,36–40]. A second large group of studies has focused on presenting, analyzing and assessing issues such as the standard of living in the city [41], public transport [29,42–51], smart mobility [52], smart living [32], sustainable mobility [53], transport-related behavior [54] and passenger preferences [55,56].

Despite considerable interest in the subject, a research gap exists when it comes to assessing the implementation of intelligent solutions by taking into account the opinions of users as a basis for decisions regarding the functioning and development of the city of the future. What is vital to remember is that the most important entities involved in the formulation of a smart city should be citizens [9] and its implementation requires a transition from the level of strategy to project implementation. That is why it is so important to involve stakeholders both in the development of a city's strategy and in the implementation of its projects, thereby enabling integrated and comprehensive understanding and proper management [57]. The presence of committed leaders with a long-term vision is also crucial.

Therefore, the aim of this publication is to assess the impact of smart city solutions on the attractiveness and reliability of public transport in Cracow. Based on our goal defined in this way, the following research hypotheses were adopted:

1. The reliability and attractiveness of public transport in Cracow is largely influenced by the smart city solutions that are implemented;
2. Assessments of smart city solutions are determined by customer behavior;
3. The reliability of public transport in most cases enhances the attractiveness of public transport.

This article is part of a highly relevant and important academic debate. By presenting unique test results in combination with Structural Equation Modeling, our study fills an existing research gap and offers an innovative approach to the study of these types of problems. This tool allows us to create models that take into account hidden (unobservable) variables, formative variables, indirect effects and intergroup comparisons [58]. In our opinion, structural equation models are currently one of the most popular and widely used methods in the field of social research. An estimator was selected that would take into account the ordinal nature of the variables, which is strongly emphasized in the literature on structural equation models.

For the theoretical part of this study, the authors conducted a classical analysis and evaluation of the subject literature, encompassing the topics of sustainable development, smart cities, as well as previous research, reports and rankings assessing conditions in Cracow compared to other cities. The empirical part of the study is based on the results of research conducted among 631 users of public transport in Cracow. The analysis was divided into the following stages: (1) model specification, (2) model estimation, (3) model evaluation, and (4) model modification.

The following article consists of three parts divided according to topic. The first part provides a presentation of sustainable mobility as a concept of cities of the future. The second discusses the concept of smart cities, with a particular emphasis on smart mobility and implemented smart solutions, which are assessed based on the example of Krakow.

2. The Theoretical Background

2.1. The Concept of the City of the Future—Sustainable Mobility

As urbanization accelerates around the world, sustainable development also increasingly depends on the effective management of urban development [10,11,59,60]. Several key areas of sustainable urban development can be identified, e.g., improving air quality and providing everyone with access to safe, affordable and sustainable transport systems, as well as improving road safety, especially through the development of public transport.

Transport is fundamental to the functioning of all societies [61]—an effectively managed transport system ensures access to employment, healthcare, education and all other services [62]. At the same time, however, it is also one of the most polluting sectors, and the second largest source of greenhouse gases after energy and electricity production [63].

The answer to global transport challenges is sustainable transport [11,64–66]. Sustainable mobility is the target model of urban mobility. Banister lists four key elements [67]: (a) the use of state-of-the-art technologies to increase the efficiency of transport, (b) taking into account the external costs of each particular mode of transport in a city's pricing policy and reducing the demand for transport through appropriate spatial planning, (c) adjusting the division of transport tasks in favor of public transport, as well as walking and cycling and (d) personalized information for residents.

Progressive climate change has compelled the EU to revise almost its entire economic policy. In November 2019, the European Parliament declared that the climate crisis has become the main challenge of our time [68]. This in turn led to the publication in December 2019 of a set of political initiatives called the European Green Deal, i.e., the action plan of the European Commission that takes into account Sustainable Development Goals [69].

From the point of view of the subject discussed in this article, of particular importance are efforts aimed at accelerating the transition to sustainable and intelligent mobility [69]. Sustainable transport will be possible when passenger needs are prioritized by means of offering options that are cheaper, more accessible, healthier and cleaner than today. Automated and network-based multimodal mobility is also expected to play an increasing role in addition to smart traffic management systems made possible by digitization. The right mix of combined measures should aim to tackle urban congestion and improve public transport.

In June 2021, the European Parliament and the Council of the European Union adopted the Climate Law [70], which is one of the components of the European Green Deal. In line with the new Climate Law, the European Commission also adopted a climate and energy legislative package: "Fit for 55" [71]. Another key component of the European Green Deal is the transport strategy announced on 9 December 2020: "Sustainable and Smart Mobility Strategy—putting European transport on track for the future" [72].

Cities are and should remain at the forefront of the transformation towards more sustainable development. The implementation of the assumptions aimed at developing sustainable mobility in cities should be a priority for local authorities. One tool intended to support the efforts of municipal authorities and entities involved in the implementation of transport policy in cities is SUMP—Sustainable Urban Mobility Plan [73]. SUMP is a strategic and integrated approach to effectively dealing with the complexities of urban transport. It presents in comprehensive form the issues related to transport, natural environment and living conditions in urban areas. SUMP also emphasizes the need to take into account in an integrated manner all aspects of mobility (both people and goods), methods and services. As a result, what is required is a holistic view of urban mobility, one that takes into account not only the integration of various urban policies, but also the impact on mobility of various modes of transport, including private motorized transport, such as, for example, car-pooling and car-sharing systems. SUMP covers the entire "functional urban area". Contrary to traditional planning approaches, SUMP places particular emphasis on citizen and stakeholder engagement, policy coordination across sectors and extensive collaboration both between different government levels and with private actors [74].

Poland is involved in shaping urban policy at both the European and global levels. Key activities focus on the provisions resulting from the aforementioned 2030 Agenda and the New Urban Agenda. The effectiveness of cities depends on the effective, efficient and partnership-based management of development in urban areas. As a consequence, of key importance are the tasks of optimizing mechanisms of cooperation in functional urban areas, developing mechanisms of participation and promoting partnership-based participation of society in urban development. Urban policy in Poland is based on three main documents: the Strategy for Responsible Development (SOR) adopted in 2017, the National Strategy for Regional Development (KSRR) of 2019 and the National Urban Policy (KPM) of 2015 [75]. These documents set out the main areas of activities, define the most important challenges facing cities and also present a vision of city development in various degrees of detail. The need for changes in individual and collective mobility (including through the promotion of collective transport) is also addressed in the Strategy for the Sustainable Development of Transport up to 2030, which was adopted in 2019 [76]. The significant improvement in sustainable urban mobility planning that has been observed over the last dozen or so years has been possible thanks to, inter alia, the emergence and rapid development of intelligent technological solutions. These technologies have led to the creation of digital cities, which in turn have turned into smart cities.

2.2. The Concept of the City of the Future—The Smart City

According to incomplete statistics, 1000 cities can be identified around the world as having entered the path of intelligent development [3]. Despite growing interest and the publication of numerous studies), no clear conclusions can yet be drawn [9,77–86] (approximately 200,000 articles [80] are written annually). Terms such as: "wired city", "ubiquitous city", "digital city", "smart communities", "intelligent city", "information city", "technocity" and "knowledge city" are often used interchangeably. On the other hand, a systematic review of the literature on smart cities reveals the most relevant streams, i.e., "smart infrastructure", "smart economy & policy", "smart technology", "smart sustainability" and "smart health" [80]. Despite the topic's popularity, it can be seen that smart city research is fragmented and inconsistent, and its development comprises two main strands. The first focuses on "a holistic view of smart cities, while the second focuses on a technocentric understanding of the problem" [87].

Technical, social, environmental and economic factors should not only be considered when implementing modern technologies. However, this factor is undoubtedly a major driving force behind the smart city and a tool that makes cities smarter and more sustainable. This concept may apply to sustainable development, quality of life, applied ICT solutions or public services. It concerns modern spatial planning, environmental protection, effective investment aimed at the development of a city and boosting its competitiveness.

The concept is multidimensional, fuzzy and not always consistent, as a result of which there is no single definition [2,37,80,88,89], no universal model for shaping a smart city, nor a single strategy concept. The basic emphasis in the smart city concept is on enhancing the quality of life of a city's inhabitants, improving the city's functioning and on the more effective use of available resources in shaping urban space. Moreover, as is rightly noted by Hodžić and Paleka [2], a very important determinant is the degree of innovative capacity in the local public sector.

According to the subject literature, the concept of the smart city encompasses six areas: a smart economy, a smart environment, smart people, smart living, smart governance and smart mobility [85,90–94]. Figure 1 presents the above-mentioned components reflecting different aspects of urban life together with examples of different factors.

It is important to note that the above areas should be treated as an interconnected whole and measurable benefits from smart cities can only be achieved if each of these planes of activity are geared towards integration with the others. It is difficult to add value if the dimensions of the entire system function in isolation. Moreover, as V. Albino [85] observed, these "dimensions are related to traditional regional and neoclassical theories of urban growth and development".

In a broad sense, a smart city comprises three integral elements: technology, people and institutions [88,95]. Technological factors include all ITC technology solutions that improve urban subsystems and support transport infrastructure. Real-time data collection allows for in-depth analyses that enhance optimal and effective decision-making. Mobile applications greatly facilitate users' access to information. Institutional factors include the management activities of the city authorities and other decision makers. This group includes all legal acts, as well as institutions established to improve the quality of life. Another important factor is efficient communication with stakeholders and taking their opinions into account in the decision-making process. The remaining human factors include a skilled and educated society, the ability to organize prosocial activities, tolerance for ethnic and cultural differences as well as an active public life.

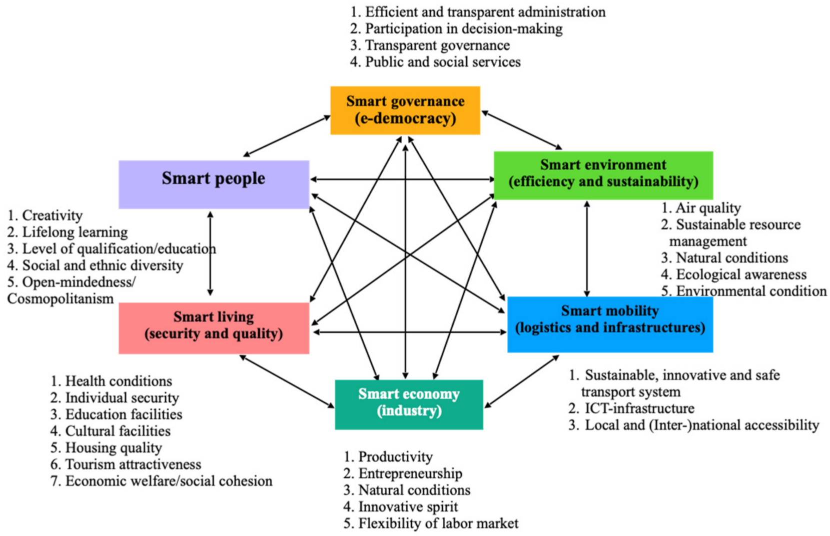

Figure 1. Smart city dimensions with related aspects of urban life and indicators. *Source: prepared by the author*.

As a consequence, a smart city is a city that invests in human and social capital, and its road and transport infrastructure promotes sustainable development and increases the quality of life. It is a continuous process of searching for innovative solutions, which in turn make it possible to respond to the challenges of tomorrow as well as ensure the effective management of natural resources in general and participatory management [81,96,97]. Nowadays, the introduction of intelligent solutions is essential, and in the case of urban development it constitutes one of the most promising concepts and visions of the future.

3. The Concept of the Idea of a Smart City—The Case of Cracow, Poland

Cracow is a city with excellent development, cultural and economic potential. Repeatedly singled out for distinction in numerous rankings, it was included in the top twenty "TOP 100 Super Cities", as one of the best destinations for the modern business services sector in Europe [17,18,98] [as well as the most important academic center in Poland. Nowadays, the city is facing many civilizational challenges that are mobilizing it to undertake continuous development. Its specific geographic location, causing excessive emissions of air pollutants [24], as well as the compact central structure of the city zone—a distinctive feature of historic cities in Europe—which limits the amount of space for extensive ring roads and larger parking complexes [99], make the implementation of intelligent solutions even more of a necessity [32,100].

For many years, Cracow's city government has been implementing a strategy aimed at building an intelligent and modern metropolis based on its scientific and academic potential, while maintaining a unique historical and cultural heritage, in which the idea of a smart city is one of the priorities of its development and future [5,14,40,43,52,101]. This idea was initiated with the preparation and adoption of a sustainable transport policy in 1993, the overarching goal of which was to create conditions for the efficient and safe movement of people and goods while limiting their harmful impact on the natural environment and living conditions of the inhabitants, as well as improving transport accessibility within the city as well as in the metropolitan area, the voivodeship and the country as a whole in conditions of sustainable mobility in the urban transport system. This document was part of the local development strategy and took into account the assumptions of the Sustainable Urban Mobility Plan (SUMP) and was updated in the following years [101–104].

Cracow is an example of a smart city that tries to combine day-to-day management in its functional urban area with strategic thinking that takes into account contemporary global challenges. The actions taken by the city authorities have been consistent and set the right path of development typical of a smart city. Their impact has been unquestionably positive, but their scale remains insufficient when compared to "leader" cities., which represent role models for smart cities (e.g., London, Singapore, Barcelona, Helsinki, New York, Tokyo, Amsterdam).

The implementation of the smart city concept can be evaluated on the basis of various rankings and research results. However, due to the lack of a single unified methodology, the results vary and depend on the adopted procedure, indicators, the availability of statistical data and socio-economic conditions [5,29,32–39]. There are many studies describing the methods used to assess the degree of implementation of the smart city concept [105–108], which have yielded varying results. However, this problem is not of interest in this publication, but only informs us that, based on various criteria, Cracow is not included in all rankings [109–113]. It is worth noting that the city appears in an important report [35] assessing the implementation of the smart city concept in six areas (smart economy, smart environment, smart people, smart living, smart governance and smart mobility). Unfortunately, only in the case of smart living did it achieve results above the European average. In the case of the other criteria, it scored below the average. It should be noted, however, that the city scores higher than all other Polish cities [114]. In another interesting comparison [34], Cracow ranks 58th out of 109 analyzed cities in terms of the ability of urban technology to improve life. According to this report, the most pressing issues requiring improvement are air pollution, traffic congestion, a limited supply of affordable housing and security. When it comes to assessing the technology used to improve the quality of travel around Cracow, the city achieved its best scores in online ticket planning and sales, the use of free parking space applications, bike rental and car-sharing applications.

It should also be pointed out that no Polish city is implementing the smart city concept in all six areas [32,35,38] and the results so far indicate that Cracow is the leading Polish urban center in terms of the progress it has made. This is a consequence of activities carried out by city managers in connection with building infrastructure and preparing the legal regulations [115] enabling such projects.

Subsequently, the various issues connected with the smart city in general will be narrowed down to one specific area—smart mobility.

The development of public transport in Cracow has been shaped by various strategic objectives [30], the city's transport policy [116], the assumptions of sustainable development [117] and EU guidelines [61,69,118–121].

The analysis [30] showed that smart mobility offers Cracow opportunities in terms of modernizing, expanding and integrating its transport systems, in particular through the development of collective transport subsystems, the construction of a Fast Agglomeration Railway and the rapid development of information technology. It is also important to be aware of the dangers arising from, inter alia, ongoing and uncontrolled suburbanization, an unevenly developed transport system, increasing traffic volume in the city and the absence of adequate legal tools restricting the entry of vehicles in the city center.

4. Current Activities Connected with the Smart City in Cracow: Smart Mobility

In view of the importance of implementing smart mobility and sustainable mobility in the Cracow transport system, as well as the assumption that smart mobility consists of ITC transport and tools, i.e., intelligent transport networks, integrated transport and logistics systems, based mainly on clean energy, the authors decided to present the actions pursued in this area up until now in the following categories:

1. Measures for improving and integrating public transport:
    - The construction of transport nodes and transfer hubs and the creation of a map of public transport nodes;
    - The creation of an integrated database (internet platform) providing access to information on regional transport departures, including dynamic information displays at all major transfer points;
    - Implementation of an integrated electronic ticket system (ticket integration);
    - The launch of the Cracow City Card and the introduction of travel planners available on the internet and via mobile applications (JakDojade.pl, E-Podrónik.pl, Transportoid, MobileMPK) [46];
    - The development and implementation of changes in the first paid parking and organic traffic zone in Poland [122] and the construction of car parks integrated with the public transport system together with Park & Ride and Bike & Ride [123];
    - The launch of an internet search engine for connections and a mobile application enabling fully coordinated timetables in transport hubs;
    - The creation of special separate lanes for buses (bus lanes);
    - The construction of turbo roundabouts with traffic light systems, based on a model unique in Europe [124];
    - Raising the surface of bus and tram stops, reducing the difference in levels and building combined tram and bus lanes;
    - Promoting a car- and bike-share model and introducing transport solutions for people with reduced mobility [5].
2. Equipping rolling stock with modern technology and improving the organization of transport. Modern technology is playing an increasingly important role in supporting traffic planning and management in the city, which is why the implementation of Intelligent Transport Systems (ITS) is an important component of such a strategy and includes:
    - A Tram Traffic Supervisio System (TTSS), which is used to monitor the operation of public transport, provide detours in the event of difficulties and breakdowns and inform passengers on an ongoing basis using electronic passenger information displays located in places with high pedestrian traffic, at road junctions and inside vehicles. The system also provides tools for preparing timetables, supervising and analyzing historical data and identifying aspects of timetables requiring improvement, as well as changes in the organization of traffic and the operation of traffic lights [125,126];
    - A Local Traffic Control System (UTCS—Urban Traffic Control System), mainly used to regulate car and pedestrian traffic. Such a dynamic traffic-light system ensures that traffic lights will turn green depending on the number of vehicles on the road as well as their speed and the mode of transport (tram), involved. Smart intersections require improvement, including with regard to pedestrian and bicycle traffic, and should ensure the synchronization of green lights at subsequent intersections [25]. UTCS has helped increase traffic flow on the city's main thoroughfares by 25 percent [125];
    - Real-time tracking of a vehicle's position using GPS transmitters;
    - Modernizing the city's rolling stock by adapting it to new requirements (e.g., replacing the drive system so as to reduce traction energy consumption, as well as purchasing rolling stock equipped with electric energy recuperation systems). All buses and trams are low-floor vehicles, equipped with air conditioning, ticket machines and a modern dynamic information system for passengers with USB charger ports [127].
3. Environmental actions:
    - Cracow ranks first in Poland in terms of electromobility solutions implemented in public transport [127,128] and possesses the largest fleet of electric buses in

Poland, although the share of electric buses in its fleet as a whole is still low [129]. The introduction of a fleet of electric and hybrid buses that meet the highest emission standards is a very important goal in Cracow's development strategy and is a significant step towards the paradigm of sustainable mobility in terms of environmental protection and transport. The city's plans assume that zero-emission vehicles will constitute one third of the Cracow bus fleet [127]. On the other hand, the new challenge for Cracow's electromobility is to integrate and optimize existing solutions in terms of the costs of its operation [130];

- Construct a rolling stock wash facility using rainwater [127];
- Actively promote initiatives and projects aimed at reducing exhaust fumes (e.g., by encouraging residents to use bicycles, organizing a Park(ing) Day, and promoting the European Sustainable Transport Week, the aim of which is to change transport habits [22].

4. Other Actions—developing and promoting the use of cycling infrastructure as an alternative means of public and private transport. At the same time, it should be emphasized that the development of infrastructure is behind schedule from the perspective of the provisions of strategic and planning documents, and the network remains disjointed, which is mainly due to the dispersion of road investments in the city space, accompanied by investments in bicycle infrastructure [131].

One issue that cannot be overlooked in any discussion of smart mobility is that of Internet access, which is an important feature of this concept. Due to the uneven distribution of access to the Wi-Fi network, which encompasses 21 urban hot spots mainly concentrated around the city center and municipal institutions (schools, museums), further expansion is necessary [32].

5. Methodology

In accordance with the aim of this study, the authors assumed that their target group would comprise users of public transport in Cracow who were of working age. The empirical research was carried out in December 2019 using a diagnostic survey, for the needs of which a questionnaire for the CAWI (Computer Assisted Web Interview) [132] internet questionnaire was prepared and posted on the social profile of the Cracow Communication Platform—PKK website.

The socio-economic features of the participants are presented in Table 1. Females accounted for 60% of participants, and males 40%. Those in paid employment constituted 40% of the total, while almost 59% were students and pupils. The largest group in terms of age (67.5%) comprised young people aged 15–24 followed by respondents aged 25–34 (24%).

Table 1. Socio-economic characteristics of the participants.

Factor	Subgroups	Number of Participants	Percentage
Gender	Female	377	59.75%
	Male	254	40.25%
Age	15–24	426	67.51%
	25–34	154	24.41%
	35–44	42	6.66%
	45–54	7	1.11%
	55–64	2	0.32%
Professional status	Student/pupil	370	58.64%
	Not working	8	1.27%
	Working	249	39.46%
	Retired/pensioner	4	0.63%

Noteworthy is the very large sample of the survey, comprising 631 users, who were asked about different aspects of transport, such as frequency of travel and modes of transport used (Table 2).

Table 2. Characteristics of users' preferences regarding the use of public transport in Cracow.

Factor	Subgroups	Number of Participants	Percentage
Transport type	Tram	256	40.57%
	Bus	171	27.10%
	Multimodal	204	32.33%
Average time of using public transport	Up to 5 min	5	0.79%
	5–15 min	87	13.79%
	16–30 min	247	39.14%
	31–45 min	160	25.36%
	45+	132	20.92%
The frequency of using public transport	Every day	444	70.36%
	A few times a week	108	17.12%
	Several times a month	46	7.29%
	Once a month	15	2.38%
	Less than once in a month	18	2.85%

It is also important to note that 70% of the respondents use collective transport on a regular basis (every day) and the most popular modes of transport mentioned by the respondents were the tram (41%) and multimodal solutions (32%). The bus was chosen by less than 27% of the respondents. The average journey time of a public transport user was approximately 30 min.

6. The Scope and Goals of the Analysis

The data included in the analysis come from a survey conducted among users of public transport in Cracow ($N = 631$). The analysis was divided into the following stages:

Stage 1—Identifying those smart city solutions implemented by MPK in Cracow;

Stage 2—Preparing the questionnaire;

Stage 3—Identifying the impact of smart city solutions in public transport on its reliability and attractiveness using structural equation models.

To achieve these research goals, the following smart city solutions implemented by MPK in Cracow were identified in Stage 1:

1. An increase in the number of bus lanes;
2. Priority given to public transport vehicles at intersections;
3. The introduction of real-time information displays at tram stops informing passengers about the exact arrival time of trams;
4. The operation of traffic lights regulated by traffic volume (green lights last longer on roads with more traffic);
5. The introduction of low-emission fleets (hybrid and electric);
6. Free public transport when air pollution levels are high;
7. The introduction of a Cracow City Card;
8. The launch of an application ("Jakdojade") designed to make getting around the city by public transport easier;
9. The introduction of a function enabling passengers to buy tickets by phone.

The survey prepared for the research comprised the questions presented in Table 3.

Table 3. Socio questionnaire.

Questions	Answers	Observable Variable
How often do you use Public Transport in Cracow?	Every day A few times a week Several times a month Once a month Less than once a month	FU
How long does your journey take on average by public transport?	Up to 5 min 5–15 min 16–30 min 31–45 min Over 45 min	TT
To what extent have newly implemented transport solutions improved the quality of public transport services?		
1. An increased number of bus lanes	Very significantly Significantly Slightly Little impact No impact	TF1
2. Priority given to public transport vehicles at intersections		TF2
3. Traffic light operation regulated by traffic volume		TF3
To what extent have ecological solutions improved the quality of public transport services?		
1. The introduction of a low-emission fleet (hybrid and electric)	Very significantly Significantly Slightly Little impact No impact	ES1
2. Free public transport when air pollution levels are high		ES2
To what extent have newly introduced facilities for passengers increased the quality of public transport services?		
1. The introduction of real-time information displays at bus and tram stops informing passengers about the exact time of arrival of trams	Very significantly Significantly Slightly Little impact No impact	PF1
2. The introduction of the Cracow City Card		PF2
3. Introduction of an application ("Jakdojade") that makes getting around the city by public transport easier		PF3
4. Possibility of buying tickets by phone		PF4
How do you rate the reliability of public transport in Cracow?	Very good Good Average Bad Very bad	
1. Punctuality		TR1
2. Travel time		TR2
3. Frequency of travel		TR3
How do you rate the attractiveness of public transport in Cracow?	Very good Good Average Bad Very bad	
1. Ticket prices		TT1
2. Comfort of travel		TT2
3. Crowding		TT3
4. Distances between stops		TT4

The last stage of the analysis involved identifying the impact of smart city solutions on the reliability and attractiveness of public transport.

7. Research Results—Structural Equation Models

Structural equation models provide a multi-equation method for describing the relationship between latent and observable variables. Observable variables are used to measure and define latent variables. On the other hand, the quality of a model is measured by reconstructing the covariance matrix of observable variables based on the postulated theoretical model.

It should be pointed out that all the variables used in the analysis are on the ordinal scale. The most popular method for addressing the categorical nature of the data is the diagonally weighted least squares (DWLS) estimator based on the polychoric correlation matrix [133]. As a consequence, in order to estimate the parameters of the defined model, the authors used the WLSM estimator in the lavaan package, which employs the diagonally weighted least squares (DWLS) method to estimate model parameters by means of a full weight matrix to compute robust standard errors, as well as a mean- and variance-adjusted test statistic [134].

Structural equation models were used to verify the following research hypotheses.

- The reliability and attractiveness of public transport in Cracow is largely determined by the implemented smart city solutions;
- Smart city solutions can be assessed on the basis of customer behavior;
- The reliability of public transport in most cases enhances the attractiveness of public transport.

The analysis was divided into the following stages:

1. Model specification;
2. Model estimation;
3. Model evaluation;
4. Model modification.

In the first step, the specification of the model was based on the theory and results of previous research. The model includes 6 latent and 18 observable variables. The specification of factors and their measuring variables are presented in Table 4.

Table 4. Specification of factors and their measuring variables.

Latent Variable	Measurement Variables (Observable)
Customer behavior—CB	Frequency of use—FU Traveling time—TT
Impact of implemented ecological solutions on the quality of public transport—ES	Low-emission fleet—ES1 Free public transport when air pollution levels are high—ES2
Impact of implemented transport facilities on the quality of public transport—TF	The increased number of bus-belts—TF1 Priority for public transport vehicles at intersections—TF2 Traffic light regulation depending on the traffic volume—TF3
Impact of implemented passenger facilities on the quality of public transport—PF	Real-time information boards at stops—PF1 Cracow City Card—PF2 Application (“Jakdojade”)—PF3 Buying tickets by phone PF4
Reliability of public transport—TR	Punctuality—TR1 Traveling time—TR2 Frequency of travel—TR3
Attractiveness of public transport TA	Ticket price—TT1 Comfort of travel—TT2 Crowding—TT3 Distances between stops—TT4

The reliability of the theoretical constructs was first checked for the constructed measurement model. For this purpose, the cfa function from the lavaan package was used to determine the confirmatory factor analysis model (CFA model), after which the reliability function from semTools package was used to calculate Cronbach’s alpha based on the CFA model. The results for reliability measured as Cronbach’s alpha are presented in Table 5. According to Tavakol and Dennick, Cronbach’s alpha above 0.60 is considered tolerable [135]. As the results show, all the structures except customer behavior (CB) show acceptable values for Cronbach's alpha.

Table 5. Reliability measured by Cronbach's alpha.

Factor—Latent Variable	Cronbach's Alpha
Customer behavior—CB	0.329
Impact of implemented ecological solutions on the quality of public transport—ES	0.665
Impact of implemented transport facilities on the quality of public transport—TF	0.617
Impact of implemented passenger facilities on the quality of public transport—PF	0.670
Reliability of public transport—TR	0.737
Attractiveness of public transport TA	0.729

In the next step, two structural equation models were created based on the defined constructs:

1. Model I—which includes all the defined constructs.
2. Model II—which includes constructs for which Cronbach's alpha is at an acceptable level.

The form of the models implemented in the R program in the lavaan package are presented in Table 6.

Table 6. Models implemented in R.

Model I	Model II
model_I <-	model_II < -
'# Measurement part of the model	'# Measurement part of the model
CB = ~FU + TT	
ES = ~ES1 + ES2	ES = ~ES1 + ES2
TF = ~ TF1 + TF2 + TF3	TF = ~TF1 + TF2 + TF3
PF = ~ PF1 + PF2 + PF3 + PF4	PF = ~PF1 + PF2 + PF3 + PF4
TR = ~ TR1 + TR2 + TR3	TR = ~TR1 + TR2 + TR3
TA = ~ TT1 + TT2 + TT3 + TT4	TA = ~TT1 + TT2 + TT3 + TT4
# Structural part of the model	# Structural part of the model
TA~TR	
TR + TA~ES + TF + PF	ES + TF + PF~TR + TA
ES + TF + PF~CB'	TA~TR'

To verify the research hypotheses, the following relationships, presented in Figure 2 for Model I and Figure 3 for Model II, were defined in the structural model:

1. The impact of consumer behavior (CB) on the overall assessment of implemented ecological solutions (ES), public transport facilities (TF) and passenger facilities (PF)—Model I;
2. The impact of implemented smart city solutions (CB, ES, PF) on the overall assessment of the reliability (TR) and attractiveness (TA) of public transport in Cracow—Model I and Model II;
3. The impact of the reliability of public transport (TR) on the attractiveness (TA) of public transport—Model I and Model II.

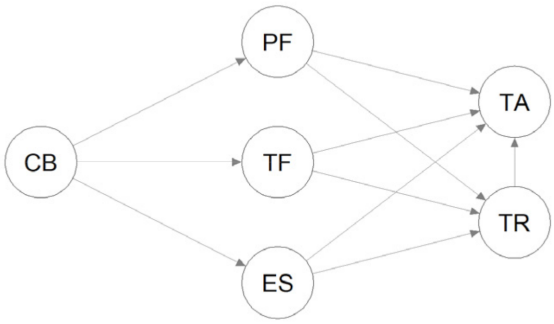

Figure 2. Path diagram of a multiple regression—Model I.

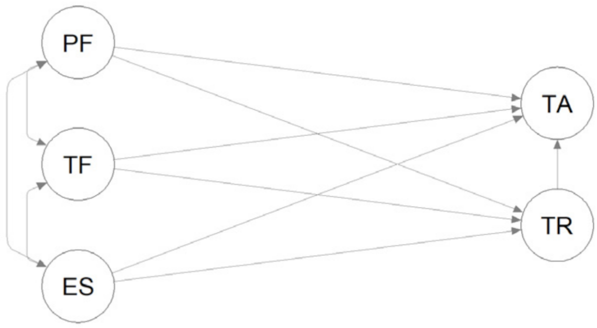

Figure 3. Path diagram of a multiple regression—Model II.

The parameters of the defined model were determined on the basis of the WLSM estimator. The data were analyzed using the lavaan package function sem.

Tables 7 and 8 show the influence of individual exogenous factors on latent variables.

Table 7. Results of Model_I—Latent Variables.

	Estimate	Std.Err	z-Value	P(>|z|)	Std.lv	Std.all
CB	=~					
FU	1.000				0.196	0.196
TT	0.294	0.258	1.138	0.255	0.058	0.058
ES	=~					
ES1	1.000				0.617	0.617
ES2	1.312	0.098	13.315	0.000	0.810	0.810
TF	=~					
TF1	1.000				0.574	0.574
TF2	1.300	0.125	10.414	0.000	0.747	0.747
TF3	1.039	0.101	10.267	0.000	0.597	0.597
PF	=~					
PF1	1.000				0.612	0.612
PF2	0.988	0.081	12.142	0.000	0.605	0.605
PF3	0.946	0.081	11.649	0.000	0.579	0.579
PF4	0.923	0.081	11.471	0.000	0.565	0.565
TR	=~					
TR1	1.000				0.643	0.643
TR2	1.075	0.088	12.243	0.000	0.691	0.691
TR3	1.193	0.092	12.953	0.000	0.767	0.767
TA	=~					
TT1	1.000				0.530	0.530
TT2	1.549	0.119	13.018	0.000	0.820	0.820
TT3	1.393	0.111	12.587	0.000	0.738	0.738
TT4	1.126	0.105	10.741	0.000	0.597	0.597

Table 8. Results of Model_II—Latent Variables.

	Estimate	Std.Err	z-Value	P(>∣z∣)	Std.lv	Std.all
ES	=~					
ES1	1.000				0.614	0.614
ES2	1.323	0.098	13.470	0.000	0.812	0.812
TF	=~					
TF1	1.000				0.574	0.574
TF2	1.304	0.126	10.324	0.000	0.748	0.748
TF3	1.041	0.102	10.228	0.000	0.597	0.597
PF	=~					
PF1	1.000				0.611	0.611
PF2	0.980	0.081	12.138	0.000	0.598	0.598
PF3	0.962	0.083	11.653	0.000	0.588	0.588
PF4	0.947	0.082	11.603	0.000	0.578	0.578
TR	=~					
TR1	1.000				0.643	0.643
TR2	1.079	0.088	12.276	0.000	0.694	0.694
TR3	1.189	0.091	13.000	0.000	0.764	0.764
TA	=~					
TT1	1.000				0.533	0.533
TT2	1.538	0.117	13.140	0.000	0.820	0.820
TT3	1.379	0.109	12.697	0.000	0.736	0.736
TT4	1.119	0.103	10.840	0.000	0.597	0.597

The results of the analyses presented in the tables show that all the parameters of Model II are significant at a level of $p = 0.05$. When analyzing the results for Model I, it should be indicated that the first parameter, i.e., customer behavior (CB), is not statistically significant and the influence of individual exogenous factors on latent variables is low (0.196 for FU and 0.058 for TT).

To test the goodness of fit of the models the following fit indices were used:

1. Comparative Fit Index (CFI);
2. Tucker–Lewis Index (TLI);
3. Root Mean Square Error of Approximation (RMSEA);
4. Standardized Root Mean Square Residual (SRMR).

Based on the literature, it was concluded that the model is considered to be a good fit if CFI is above 0.9, TLI is above 0.9, while RMSEA values of up to 0.08 are accepted as representing a reasonable fit [136] and SRMR up to 0.08 [137]. The results of the model fitting are presented in Table 9.

Table 9. Goodness-of-fit measures.

Model Fit Indices	Cut-off Value	Model I	Model II
Robust Comparative Fit Index (CFI)	>0.9	0.900	0.927
Robust Tucker–Lewis Index (TLI)	>0.9	0.877	0.906
Robust Root Mean Square Error of Approximation (RMSEA)	<=0.08	0.086	0.084
Standardized Root Mean Square Residual (SRMR)	<=0.08	0.083	0.074

Based on the results, it can be seen that Model II is better fitted than Model I. As a consequence, further analysis focused only on Model II. Due to the fact that not all fit indicators for Model II achieved acceptable values, an attempt was made to modify the model. For this purpose, the modindices function from the lavaan package was used.

Based on the results obtained, the analyzed model enables correlations to be established between the residual variances of the two observed variables. The rationale for doing so is the authors' belief that the two variables have something in common that is not captured by the latent variables. Correlations between the following variables were introduced into the model:

1. Comfort of travel (TT2) and crowding (TT3)
2. An increased number of bus lanes (TF1) and priority given to public transport vehicles at intersections (TF2).

The final form of the model is presented in Table 10.

Table 10. Modified Model II.

Model II
> model_II<- '# Measurement part of the model ES = ~ES1 + ES2 TF = ~ TF1 + TF2 + TF3 PF = ~ PF1 + PF2 + PF3 + PF4 TR = ~ TR1 + TR2 + TR3 TA = ~ TT1 + TT2 + TT3 + TT4 # Structural part of the model TA~TR TR + TA~ES + TF + PF TT2 ~~ TT3 # Cov(TT1, TT2) to be estimated TF1 ~~ TF2 # Cov(TF1, TF2) to be estimated '

First, the authors checked to what extent introducing the correlation between the observable variables into the model improved the fit of the model. A summary of the fit results for Model II before and after the modification are presented in Table 11.

Table 11. Goodness-of-fit measures for modified Model II.

Model Fit Indices	Cut-Off Value	Model II after Modifications	Model II before Modifications
Robust Comparative Fit Index (CFI)	>0.9	0.958	0.927
Robust Tucker–Lewis Index (TLI)	>0.9	0.945	0.906
Robust Root Mean Square Error of Approximation	<=0.08	0.064	0.084
Standardized Root Mean Square Residual	<=0.07	0.060	0.074

It should be noted that all the fit indicators were at a satisfactory level. Therefore, Model II was considered to be a good fit for the data. The structural and measurement model was presented in Figure 4.

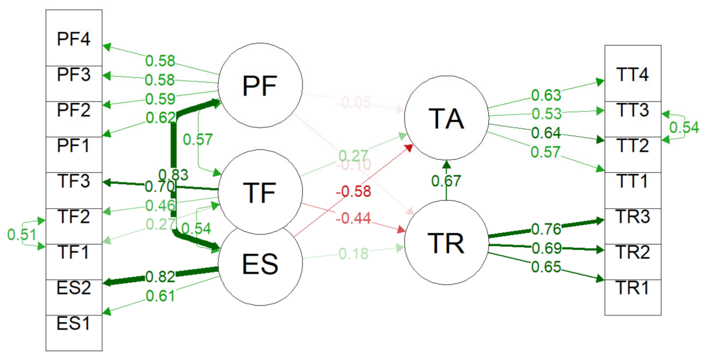

Figure 4. Structural and measurement model.

First, the authors analyzed the influence of observable variables on the latent variable. The results are presented in Table 12. Model II features relatively strong and statistically significant relationships between latent exogenous variables and their observable variables.

Table 12. Influence of observable variables on the latent variable.

	Estimate	Std.Err	z-Value	P(>|z|)	Std.lv	Std.all
ES	=~					
ES1	1.000				0.608	0.608
ES2	1.345	0.098	13.741	0.000	0.819	0.819
TF	=~					
TF1	1.000				0.266	0.266
TF2	1.735	0.311	5.572	0.000	0.462	0.462
TF3	2.636	0.646	4.081	0.000	0.702	0.702
PF	=~					
PF1	1.000				0.619	0.619
PF2	0.957	0.077	12.386	0.000	0.592	0.592
PF3	0.944	0.081	11.716	0.000	0.584	0.584
PF4	0.938	0.080	11.771	0.000	0.580	0.580
TR	=~					
TR1	1.000				0.650	0.650
TR2	1.065	0.086	12.364	0.000	0.693	0.693
TR3	1.166	0.090	12.882	0.000	0.758	0.758
TA	=~					
TT1	1.000				0.567	0.567
TT2	1.133	0.098	11.527	0.000	0.643	0.643
TT3	0.926	0.103	8.955	0.000	0.525	0.525
TT4	1.115	0.104	10.739	0.000	0.632	0.632

The most important of the ecological solutions (ES) implemented in the city is the availability of free public transport when air pollution levels are high (ES2)—0.819. An analysis of the relationships between transport facilities (TF) reveals that the most important observable variable was traffic light operation regulated by traffic volume (TF3). The relationships between the latent variables passenger facilities (PF), reliability of public transport (TR), attractiveness of public transport (TA) on the one hand, and their observable variables on the other, should also be interpreted in a positive light. The correlation between these variables and observable variables was significant. The most important variable in the case of passenger facilities (PF) is real-time information displays at bus and tram stops (PF1), in the case of reliability of public transport (TR)—traffic light regulation dependent on traffic volume (TF3) and in the case of attractiveness of public transport (TA)—travel comfort (TT2).

Table 13 presents the results for the structural part of the model. It should be noted that not all model parameters are significant at the level of p-value = 0.05.

Table 13. Structural coefficients of latent variables in relation to constructs.

	Estimate	Std.Err	z-Value	P(>|z|)	Std.lv	Std.all
TA	~					
TR	0.580	0.077	7.523	0.000	0.665	0.665
TR	~					
ES	0.194	0.199	0.971	0.332	0.181	0.181
TF	−1.076	0.340	−3.166	0.002	−0.441	−0.441
PF	−0.108	0.197	−0.547	0.584	−0.103	−0.103
TA	~					
ES	−0.541	0.187	−2.886	0.004	−0.580	−0.580
TF	0.566	0.274	2.065	0.039	0.266	0.266
PF	−0.045	0.189	−0.238	0.812	−0.049	−0.049

The results lead to the conclusion that the reliability of public transport (TR) in terms of punctuality (TR1), travel time (TR2) and frequency of travel (TR3) has a positive impact on assessments of the attractiveness of public transport (TA). On the other hand, the implemented transport facilities (TF), described by the following observable variables: an increased number of bus lanes (TF1), priority given to public transport vehicles at intersections (TF2) and traffic light operation regulated by traffic volume (TF3), do not have a positive impact on perceptions of public transport as a reliable means of transport (TR). On the other hand, the impact of newly introduced transport facilities (TF) has a positive impact on the overall assessment of the attractiveness of public transport (TA).

Finally, an analysis of the impact of ecological solutions (ES) in the city, i.e., a low-emission fleet (ES1) and free public transport when air pollution levels are high (ES2), on the attractiveness of public transport, indicated no positive relationship between these variables.

8. Conclusions

The smart city and sustainable mobility have become popular research topics in the scholarly literature. Cities play a vital role in social and economic development, and they have a tremendous impact on the environment. They also provide a source of competitiveness and yield economic and financial benefits. Nowadays, cities face a number of problems caused by, inter alia, progressive urbanization and socio-demographic changes, which lower the quality of life [138]. As a continuous process of searching for innovative solutions the "Smart city" offers a means of responding to the challenges of tomorrow. Its focus is not only on implementing new technologies, but also on the skillful use of available resources in the search for optimal solutions to emerging problems. It enables the rapid and efficient flow of information necessary for decision-making and connects all areas of city management in tasks aimed at improving the quality of life of residents. It is a central feature of sustainable urban development and covers a wide range of issues related to effective and sustainable city management, which have an impact on their energy efficiency.

Our research makes it possible to assess the impact of smart city solutions and the reliability of public transport in Cracow and verify the following hypotheses:

- The reliability and attractiveness of public transport in Cracow is largely determined by the smart city solutions implemented there—hypothesis disproved. Of all the smart city solutions implemented in the city only transport facilities have a positive impact on perceptions of the attractiveness of public transport in Cracow. This impact is limited (0.266). The transport facilities (TF) implemented in the city do not have a positive impact on perceptions of public transport as a reliable means of transport (TR). The impact of ecological solutions (ES) indicated no positive effect on the attractiveness of public transport (TA). The impact of ecological solutions (ES) and passenger facilities (PF) on the reliability of public transport (TR) and the impact of passenger facilities (PF) on the attractiveness of public transport (TA) were statistically insignificant at p-value = 0.05;
- The assessment of implemented smart city solutions is determined by customer behavior—hypothesis disproved. This construct was statistically insignificant at p-value = 0.05 and the impact of individual exogenous factors on latent variables is low (0.196 for FU and 0.058 for TT);
- The attractiveness of public transport is largely dependent on the reliability of public transport—hypothesis confirmed. The relationship is statistically significant at p-value = 0.05.

The conclusion of the research is that the implementation of such smart city solutions in the Cracow as: (1) an increased number of bus lanes; (2) priority given to public transport vehicles at intersections and (3) a traffic light system regulated by traffic volume have not had a positive impact on perceptions of the reliability of public transport in Cracow by its users.

On the other hand, the implementation of a dynamic traffic light system has boosted perceptions of its attractiveness. This may be related to the fact that Cracow is a city greatly affected by congestion and crowded streets, and despite the implementation of such solutions, users are still not satisfied with the reliability of public transport.

Additionally, research carried out by P. Budziło and D. Socała shows that the most important problems for the citizens of Cracow are road-related problems and traffic congestion [29]. However, it is also worth noting research on user satisfaction with public transport conducted by Z. Bryniarska [47], W. Starowicz and K. Gretkowska [55], which revealed that satisfaction levels are high and have been gradually increasing in recent years. In addition, passengers rate their level of satisfaction with tram services higher than with bus services. These results are dependent on the availability of stops, the frequency of services, and the reliability of connections.

The steps taken by the city's authorities to implement smart city solutions has undoubtedly increased its attractiveness for passengers. Another important aspect of the smart city worth highlighting is the ecological solutions implemented in public transport. According to the respondents, the introduction of low-emission rolling stock and the availability of free public transport on days when air pollution levels are high have not made the use of public transport more attractive.

For many years, the city authorities have taken a greater interest in the issues of environmental protection and the quality of life of the local population as well as in the need to increase the role played by low-emission rolling stock in shaping transport policy [31,116]. Hence, the results of our research are surprising. They also provide important information on the actions being taken to improve the ecological awareness of Krakow's citizens.

Moreover, as is indicated by C. Nicolas, J. Kim and S. Chi [138] those enablers responsible for putting smart city solutions into practice often encounter difficulties formulating appropriate policies for successful planning and development due to the lack of any comprehensive quantification of the effects of enablers' actions. In addition, C. Nicolas, J. Kim, and S. Chi [139] observed that the development paths of smart cities are highly dependent on urban-specific contextual conditions.

Some limitations of the present research should be noted concerning the fact that most of the respondents were young people. Therefore, it could be concluded that the model largely reflects their opinions. The reasons for such a study population structure may be that most young people in Cracow are public transport users. On the other hand, this tendency recurs in other studies evaluating urban public transport both in Cracow [45,47] and other cities in Poland [140,141] as well as in research conducted other cities around the world [142,143].

Unfortunately, due to a lack of available research on the age structure of public transport users in Cracow, the authors cannot confirm that young people actually are the dominant passenger group in the city. MPK, the Cracow Public Transport Authority, has not carried out such analyses either. Therefore, a new area of research has revealed itself, which will involve examining the structure of public transport passengers and determining whether and to what extent users' behavior and their assessment of the quality and attractiveness of public transport is determined by their age.

Nevertheless, this work is an important contribution to the discussion on smart cities and sustainable mobility in the context of public transport as well as to research assessing the value of implemented smart city solutions. The research highlights the need for comparative studies with other Polish cities to see how their citizens evaluate the attractiveness and reliability of their city's public transport systems and whether a significant improvement in sustainable urban mobility planning can be observed nationwide. It would also be interesting to compare Cracow, the pioneer in implementing the smart city concept in Poland, with the smartest cities in other countries in Europe and around the world.

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