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Scientific journal intended to combine theory and practice in the field of transport and communications, and thus the advancement of transport and communications sciences.

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Spatial Analysis of Road Safety Awareness and Traffic Accident Patterns in Urban Neighborhoods: A GIS-Based Study of Ibadan Metropolis, Nigeria

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Abstract Road accident occurrences are a universal and worldwide phenomenon. This is so because accidents happen on all categories of roads, which include street roads, express roads, tared and untarred roads, among others. The study analyses accidents in the neighborhood roads, like the streets, minor link roads, or minor roads that link major areas together, and identifies road traffic accident locations to assess the road users' safety awareness levels in the Ibadan metropolis. Data were sourced from the police traffic department. This data includes streets where accidents have occurred in the metropolis (2018-2023), and the type of vehicle involved. GPS (global positioning system) was used to take coordinates of the streets and locations. The city was divided into zones based on the magnitude of accident occurrence, and questionnaires were used to evaluate road users' road safety awareness levels for each zone. These were rated as percentages. The level of awareness of the presented road signs and the frequency of accidents in each zone were correlated to establish the relationship. ArcGIS 10.8 for spatial analysis and SPSS 17.0 for correlation analysis. Descriptive statistics data were presented using tables, charts, and maps.

The analysis reveals the magnitude of accident occurrence across the zones. The correlation analysis shows a correlation of 0.827; p-values are $< .01$. It indicates a strong correlation between accident occurrences and the level of awareness and use of road signs and symbols. The distribution of accident incidences across Ibadan city is clustered with the p-value at 0.01, which is greater than the z-score of -2.52. It was also observed that motorcycles are the most involved in accidents within the metropolis, and that accidents increase as we move away from police stations. Causes of accidents are seen to be different across the metropolis, with low traffic safety education ranking the highest.

The study therefore recommends re-educating road users on how to use the road and obey road signs and symbols as a way to reduce accident incidences within the metropolis. The presence of control agents like the police, the road safety corps, and the Oyo state traffic management personnel should be encouraged.

Keywords Cordon, Road Safety, Accident, Georeferencing, Safety consciousness

JEL R41, R42, D81, C21

1. Introduction

Road traffic safety awareness refers to methods and measures for reducing the risk of a person using the road network from being killed or seriously injured. The users of a road include pedestrians, cyclists, motorists, their passengers, and passengers of on-road public transport, mainly buses and cars. Safe road is now about providing a road environment which ensures vehicle speeds will be within the human tolerances for serious injury and death wherever conflict points exist. Kirmiziloglu (2010) posited that since the number and quantity of vehicles on roads has increased due to technological and economic, development in recent years. As a result of this increase, traffic has been one of the most important parts of our daily lives as people spend more time in traffic, thereby forcing drivers and other road users to face a higher risk of traffic accidents.

Worldwide more than 1.25 million people lose their lives annually due to traffic crashes. Everyday nearly 1,049 people under the age of 25 lose their lives in traffic accidents World Health Organization (2004). Traffic signs are the oldest and most commonly used traffic control device (TCD). These signs convey messages in words or symbols and erected to regulate, warn, or guide the road users. Traffic signs are commonly used traffic safety tools, mainly developed to provide crucial information in a short time to support safe drive; but the success depends on their comprehensibility by the drivers (Tuydes-Yaman, 2012).

The American National Standard Institute (ANSI Z535.3-2011) advises that traffic signs should meet 85%, while the Organization of International Standardization (ISO 3864) pegged its own at 67%. Traffic signs in relation with congestion and traffic accident occurrences have been a topic of considerable interest to researchers in the past few decades.

This research was undertaken to access the drivers' and other road users personal characteristics in understanding of traffic signs in Ibadan city, the capital city of Oyo state. The study of the role of road user characteristics in understanding traffic signs in Ibadan is of great importance since traffic accident still occurrences along the express way and other neighborhood road.

1.1. Statement of the Problem

In spite of the studies and researches made into road traffic crash occurrences and road safety awareness levels, it appears that the benefits are not reflected in the society as there is still the feeling of insecurity among road users no matter the category they belong, the issue is why should it be so? From the literatures accident analyses have been carried out with data analysis in the form of statistics, mathematics, tables and graphs. The effect of highways and express Road Traffic Accident Injuries on Productivity in Nigeria, and also examined the spatial variation of road traffic accident casualties in Nigeria. The trends and patterns of fatal road accidents along major highways in Nigeria. According to Makinde and Opeyemi (2019), there have been alarming cases of traffic accidents on roads, which they attributed to the recklessness and low level of literacy about the use and interpretation of road signs and symbols.

Road accident occurrences are a universal and worldwide phenomenon, this is because accidents happen on all categories of roads, which include street roads, express roads, tared and untared roads, among others. Effort has been made over the years in the literature to emphasize the need for safety awareness in the use of road transport (express/highway roads). Emphasis before and now shows that road accident analysis on the highways and express roads are high. However, much attention have not been on the analysis of accidents in the neighborhood roads like the streets, minor link roads or minor roads that links avenues, estates and districts within a city. Since traffic accident is a geographical phenomenon that occurs in relation to place, time and environment this work is conducted to analyze the neighborhood road traffic accident in Ibadan city.

1.2. Aim and Objectives of the Study

The aim of this study is to analyse the relationship between the level of road safety awareness and the rate of Accident occurrences in Ibadan city of Oyo State. The specific objectives intended to be achieved at the end of this study is to examine the types of vehicles that is involved in traffic accident in the study area and to spatially analyse the safety awareness levels of road users in the study area.

2. Literature Review

There is obviously no single category of "road user". In today's motorized society virtually every one among us at some time has to use the road whether as a child or adult, pedestrian, driver, motor cyclist and so on. The traffic system places high demands on all road users. If such demands are

not mastered, or are dealt with wrongly, a collision becomes possible. The way we cope with all the demands imposed upon us by the traffic system depends not only on the way we perform, but also on the way we behave. Naturally, road user performance and road user behaviour are inextricably intertwined.

Since motor vehicles became popular and the number of accidents started to raise, approaches to making road use safer have been based on a perception that accidents are failures of skill, and that the safety of a road user is mainly determined by the level of skill applied in response to the demands that are faced. Accordingly, the general strategy has long been to increase road-use skills and decrease the demands placed on road users by the environment.

Every transport activity is designed to meet the need of the customer and is therefore incomplete until the concept of "safe arrival" by both the passenger or goods are met, Ndikom (2008). It involves authorities to put in place necessary facilities, procedures, personnel as well as machinery that would ensure safe arrival and reduce accident. It therefore makes it mandatory and essential for all road users to be safety conscious. Some of the measure to be adopted in ensuring the safe arrival of road users may include creation of walk way, cycle path, pedestrian bridges, initiate a permit system for all motor users (car, motor cycle and bicycles) encourage the use of reflective patches, traffic light among others.

2.1. Road traffic safety

Safety concerns in transportation planning are fundamental, as evidenced by a comprehensive examination of plans across 35 metropolitan areas globally (Peng & Wang, 2011). The critical importance of ensuring safety within road networks reverberates due to its extensive influence on various dimensions of people's lives. The safety performance of road transport systems hinges on a multitude of factors, encompassing network functionality, predictability, consistency, road environment, and traffic dynamics (Hafen et al., 2005). Rising concerns about the safety associated with automobiles and motorcycles are capturing the attention of road users and safety experts worldwide, with a pronounced focus on developing nations (Tavakoli Kashani & Arefkhani, 2018). Within this context, urban planners and traffic engineers are particularly attuned to the effects of diverse road network layouts on traffic safety, presenting a key arena for impactful interventions (Zhang et al., 2014). The sphere of urbanism and spatial planning significantly shapes traffic safety strategies, pursuing a harmonious equilibrium between requirements, opportunities, and road characteristics (Tăriță Cîmpeanu & Burlacu, 2012).

An integral metric for evaluating road safety emerges through the analysis of societal costs linked to accidents and injuries (American Association of State Highway and Transportation Officials AASHTO, 2010; Hafen et al., 2005; Herbel et al., 2010; Millot, 2004). Notably, while crashes remain relatively infrequent, they represent a modest proportion of incidents in the broader transportation landscape (Oregon Department of Transportation (ODOT) Traffic-Roadway

Section, (2021) (2021)). The severity of crashes is predominantly dictated by the most severely injured participant, prompting a structured approach for officials to prioritize safety improvements on specific road segments (Elvik, 2008; Golembiewski & Chandler, 2011; Ma et al., 2021; Schneider & Savolainen, 2011). As a pivotal initial step toward advancing traffic safety, the identification of clustered risk areas for traffic accidents assumes priority (Zhang & Shi, 2019). Within this framework, hotspot methodologies emerge as consequential tools, facilitating the orchestration of cost-effective road safety strategies to mitigate traffic accidents (Xu & Tao, 2018).

2.2. Traffic accidents spatial analysis

Road Traffic Accidents (RTAs) are unfortunate incidents that occur unexpectedly and unintentionally. The analysis of road accident data is essential for safety analysis and identifying areas with high accident frequencies of severe injuries and fatalities (Lee et al., 2005). The goal of traffic accident safety analysis is to prevent further accidents by identifying the cause of an accident or series of accidents (Bhalla et al., 2014). Studies have been conducted using spatial units and road networks to identify elements that impact traffic safety. Analyzing individual road segments is crucial for identifying factors that increase the risk of accidents and despite technical challenges, the use of road networks in traffic safety studies has increased (Á. Briz-Redón et al., 2019).

The study by Ziakopoulos and Yannis (2020) suggests that analyzing road safety indicators across spatial units of analysis is essential in the field of road safety. Spatial analysis of road crashes and their locations is important because road transport is distance-based. The use of Geographic Information Systems for Transportation (GIS-T) (Goodchild, 2000; Loo & Anderson, 2015; Shaw, 2000) and GIS Safety Analysis Tools have facilitated the analysis of traffic safety, including the prediction of areas where accidents are likely to occur (Mehta et al., 2015; Pulugurtha & Pasupuleti, 2013). Many spatial statistical tools are now available in GIS software to build complex models in a simple process and its ability to detect spatial relationships in accidents that cannot be detected by traditional methods of statistical data. Such spatial tools provide a geographical component to crash data, which helps in understanding the crashes in relation to the environment and road. The use of GIS in road management for traffic safety purposes allows for a variety of spatial analyses and graphical illustrations of the results for interpretation (Mohan Rao, 2014; Polat & Durduran, 2011).

The use of GIS technology has been extensively employed in road safety research to identify areas where accidents are most likely to occur. The Kernel Density Estimation (KDE) algorithm in ArcGIS has been used to analyze spatial data to determine the distribution of accident risk, as demonstrated by Budiharto and Saido (2012). Ouni and Belloumi (2019) suggest using spatial autocorrelation, specifically Moran's I and Getis-Ord statistics, as a powerful technique for spatial clustering to identify accident spatial patterns and hotspots. Moran's I measures spatial dependence to group areas with similar spatial patterns, while the Getis-Ord statistic provides

a singular measure of spatial correlation and quantifies the extent of clustering in the spatial arrangement (Satria & Castro, 2016). Colak et al. (2018) also supports the use of GIS technology, specifically KDE, for identifying accident-prone highways.

The systems perspective, views human performance as a function of many interacting system-wide factors. In the context of human error and road traffic crash causation, for example, it is now accepted that errors are a consequence of 'systems' failure rather than merely aberrant psychological factors within individuals. In a road safety context, elements of the system beyond road users, such as vehicle design and condition, road design and condition, road policies, and so on, all shape drivers behaviour on the road.

3. Methodology Research Design

This study is designed to use survey which involves the usage of structured questionnaire. The entire city was divided into regions with a 1 kilometer cordoned. This was achieved through the operation of the ArcGIS software tools on the map of Ibadan city, as shown in Figure 1. Questionnaires were administered to respondents within the cordoned area. The choice of these areas was based on locations with the highest frequency of accident occurrences in the period under study as provided by the police traffic department of the Nigerian police force. With 95% confident level, $p= 0.5$ and $q= 1-0.5$, acceptable error imagine is 4.5% so $d= 0.045$. The questionnaires were designed in a manner that they contain both open-ended and closed-ended questions. Section one had questions for pedestrians and cyclist (bicycle or motorcycle). Simple choice questions requiring respondent to tick their choice among the options yes or no. Section two had questions for vehicle drivers and other road users they will be required to interpret some of the road signs and symbols. Not less than twenty-four questionnaires were administered to respondents in each of the twenty zones.

This sampling design is based on the concept of the geographic pattern of traffic accident analysis, which believes that traffic accidents occur in place, time, and environment. Hence the need for cordoning the place (roads and streets).

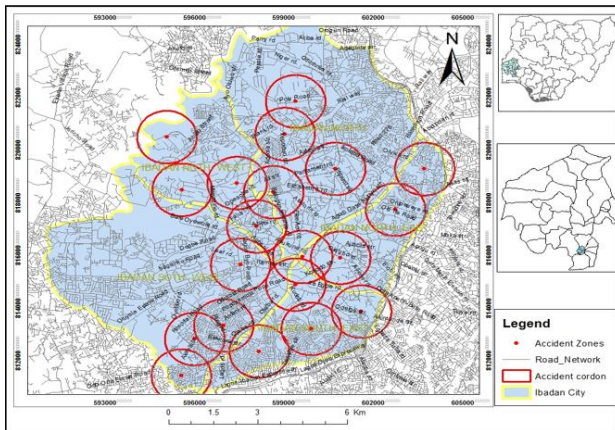


Figure 1. Map of Ibadan showing the cordoned area

3.1. Sampling Procedure

The sampling procedure that was used in this study is the stratified and simple random technique. Stratification was used to delineate the city into regions using available information from police records, applying the buffering tool in the ArcGIS 10.2. The delineated or cordoned area was visited with a questionnaire using a simple random sampling technique to pick and identify candidates for interview within the (stratified/delineated) cordoned distance of one kilometer (1km).

3.2. Sources of Data

Data for the research were sourced through primary and secondary sources.

Primary sources: the primary data used for this work were obtained from the administration of a predetermined questionnaires, direct observation and oral interviews. Forty questionnaires were administered in each zone, making a total of two hundred within Ibadan city of Oyo State. These instruments were needed to harvest information on the depth of their traffic education and understanding of the road signs and symbols.

Secondary sources: Information on traffic accidents was sourced from the police traffic records. The Nigerian transport system and the place for a vibrant traffic education system, among others, are derived from journals. Write-ups on the importance of traffic education and the need to ensure safety on roads, and the need to imbibe positive attitude and behavior among others were retrieved from the internet. The analog map of Ibadan city was also collected from the State Ministry of Lands and Survey in Ibadan, and the road map of the city was sourced from the Oyo State Ministry of Transport.

3.3. Creation of Spatial Data

The most distinguishing feature of the GIS tool is its spatial analysis capabilities; it can process data to derive new information. Accident data were collected from the archive of the Nigeria Police traffic Department State headquarters in Ibadan Oyo State. The Accident records for Ibadan city for the period of (2018-2023) were used for this study. Database (attribute data) created in a table format showing accident

type, number of occurrences, and streets/roads in the local government of occurrence. The analog map and the road map were scanned, georeferenced, and digitized in ArcGIS 10.2. A global positioning system (GPS) device shall be used to take the coordinates of the locations where accidents have occurred in Ibadan city.

3.4. Road traffic crash georeferencing

Georeferencing is the creation of a database that enables us to tie a particular event in geographical space to a location with the use of a GPS (global positioning system). As a result, streets given in the police records were divided into groups, and a table was created with spaces to record the name of the street, the point (x and y, coordinates), and the local government area using the GPS. The Spatial analysis to be carried out will include buffering analysis (cordoning), Trend Analysis, nearest neighbor analysis, and accident distance decay, as thematic maps were used to show the accident situations and their uniqueness across the local government in Ibadan city.

4. Results

On the analysis of the collected data through data acquisition from police records, questionnaires, observation, and literature review. The police traffic department records reveal streets and roads where accidents occurred in the period under review. A GPS global positioning system device was used to take the geographical coordinates of the streets. On this basis, a 1-kilometer cordoned area was established around the zones for questionnaire administration. Hypothesis testing was done using the scores from the questionnaire and the rate of traffic accident occurrence in the SPSS environment to find the correlation analysis.

The results from the questionnaire were based on 100%, and it is related to the available data on accidents from the police records and subjected to correlation analysis in the SPSS environment, which established the correlation/relationship between the level of traffic safety awareness and usage and the rate of accident occurrence in the city. Also, descriptive statistics were applied to the data collected from the traffic department of the Nigerian police, and the data is displayed using various charts and graphs in Microsoft Excel to enhance understanding.

Table 1. Survey ratings for zones (Source: field work)

Road signs understanding rating in % (x)	No of accidents (y)	Zones
95	11	Salvation Army Road
80	19	Ojo-Oba Road
79	15	Baale Akintayo Road
79	11	Elizabeth Road
78	19	Tunji Aderinlo Street
73	19	Lam Adesina Road
73	18	Amadiyya Street
72	18	Oderinlo Street
68	19	Poly Igokodo Road
65	24	Omilabu Street
65	20	Onireke Road
61	23	Agodi Gate Road
55	24	Odo-Ona Elewe Road
55	20	Akintayo Street
52	27	Plank Road
48	20	Adegun Street
45	26	Ayo Adesina Street
45	28	Poly Road
43	34	Kobomoji Street
42	24	Lanre Adepoju

Table 2. The magnitude of the accidents in the study area (Source: Police traffic department records)

LGA	Zone	Number Of Accident Cases
Ibadan North	Poly Road	28
	Plank Road	27
	Agodi Gate	23
	Elizabeth Road	11
Ibadan North East	Baale Akintayo Road	15
	Poly Igokodo Road	19
	Onireke Road	20
	Salvation Ary Road	11
Ibadan South West	Amadeyya Street	18
	Adegun Street	20
	Lanre Adepoju	24
	Odo-Ona Elewe Road	24
Ibadan South East	Omilabu Street	24
	Ojo-Oba Road	19
	Akintayo Street	20
	Lam Adasina Street	19
Ibadan North East	Tunji Adrinlo Street	19
	Ayo Adesina Street	26
	Kobomoji Street	34
	Oderinlo Street	18

Roads in Ibadan city are frequented by a great diversity of users, particularly young and old, who use different types of vehicles, as well as pedestrians, who constitute the group at highest risk of being involved in a road crash. Vehicle fleets, including trucks, minibusses, and taxis, are also growing in number. Motorcycles have become the most popular form of transport within the city. The number of motor vehicles in operation is growing rapidly, resulting in a surprising level of violence on the road. This situation is likely to worsen unless firm and coordinated measures are taken; death and injury on the roads is quite a phenomenon, an indication that the road safety awareness level is still not high enough.

4.1. The Vehicles that are involved in road traffic crashes

Table 3 shows the number of times the various types have been involved in accidents in the city in the period under review. Accidents involving motorcycles appear to be more frequent than any other type of accident in the neighborhood. In the period under review, motorcycle accidents account for 74.55% of the total accidents in the neighborhood of Ibadan city.

Table 3. Vehicles, years, and percentage of accident involvement (Source: Police traffic department)

Year	Motorcycle	Car	Lorry	Bus	Total
2003	21 (51%)	16 (39%)	NA	4 (10%)	41
2004	19 (59%)	5 (15%)	1 (3%)	7 (22%)	32
2005	60 (87%)	4 (6%)	0	5 (7%)	69
2006	25 (78%)	4 (13%)	1 (3%)	2 (6%)	32
2007	19 (59%)	5 (16%)	1 (3%)	8 (25%)	32
2008	25 (86%)	3 (10%)	0	1 (4%)	29
2009	32 (74%)	7 (16%)	NA	4 (9%)	43
2010	27 (79%)	4 (12%)	3 (9%)	1 (3%)	34
2011	19 (76%)	1 (4%)	3 (12%)	2 (8%)	25
2012	23 (88%)	1 (4%)	2(8%)	0	26
2013	20 (83%)	3 (13%)	0	1 (4%)	24
	290 (74.55%)	53 (13.60%)	11 (2.80%)	35 (9.0%)	389

The next is an accident involving cars, which accounts for 13.60%; this is followed by accidents involving buses, responsible for 9.00%, and Lorries, 2.80%. This can be attributed to the level of education of the motorcycle riders, who are mainly not well educated and lack adequate knowledge of road safety principles.

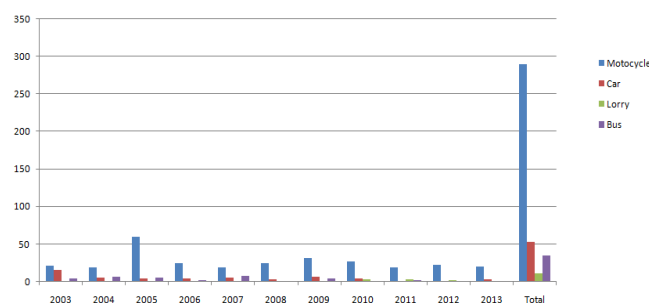


Figure 2. The years and vehicles involved in the accident

The graph in Figure 2 shows that accidents involving motorcycles were highest in the year 2005. This is because most riders are not properly trained and, as a result, do not know the traffic signs and symbols, let alone obey them. It was observed that motorcycles are the most involved in traffic accidents in the city, followed by cars, buses, and Lorries respectively. The year 2005 is seen to be the year with the highest incidence of traffic accidents, with motorcycles being the highest contributor.

4.2. Spatial Analysis of the Safety Consciousness Levels

The data in Tables 1-3 were imported into ArcGIS 10.2 for spatial analysis of accident locations in the study area. The results are presented below as diagrams and thematic maps.

Nearest neighbors analysis

This analysis helps us to find out if accident occurrences are evenly spread, distributed, or clustered in a particular region in the city. The result is shown in Figure 3.

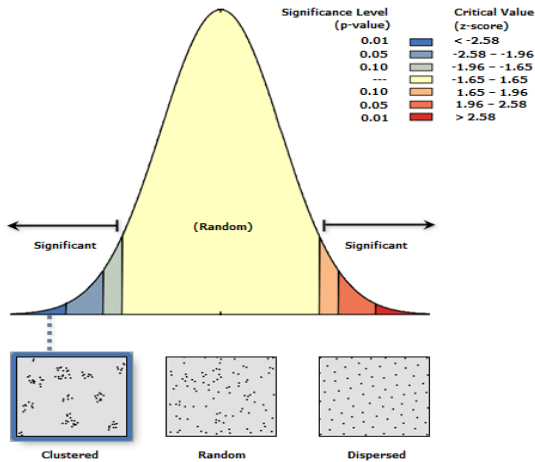


Figure 3. Spatial analysis of accident occurrence in Ibadan city.

The p-value is 0.01, which is greater than -2.52, which is the z-score. This result means that the distribution of accident incidences across Ibadan city is clustered. Implies that accident incidences are more in some areas because of the lack of presence of the enforcement agents in those areas, which has created a large distance corridor for the intending traffic offender to go unchecked and unpunished each time the rules are broken.

Distance decay analysis

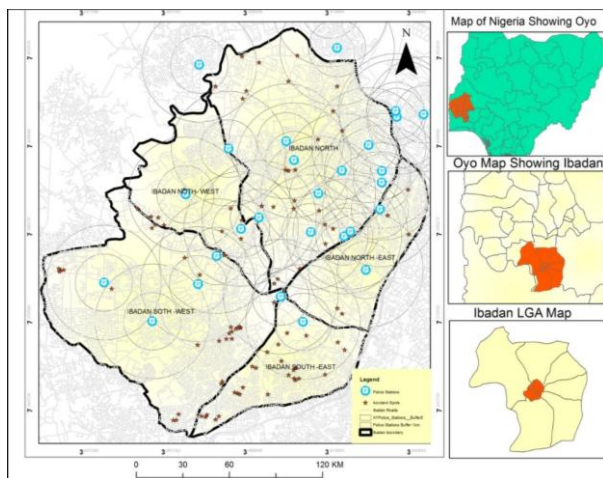


Figure 4. Map of Ibadan city showing the buffered police station.

From Table 4, of 408 accident occurrences in the police records, 52 occurred within 1 kilometer of a police station, 121 within 2 kilometers, and the rest outside 2 kilometers. And 145 happened within 3km.

Table 4. Distance decay and accident occurrence

Buffered distance	No. of Accident
1km	52
2km	121
3km	145

This means the accident rate increases as you move away from the police post or traffic regulation agents. Implies that carelessness and disobedience to traffic signs and symbols increase when enforcement agents are not in a position to sanction or arrest. Local government area in the city with fewer police stations has a higher number of accidents within the neighborhood.

Safety consciousness levels

The data at the local government level, i.e., the local governments that make up Ibadan city, are in Table 5. It was observed that some types of accidents are prevalent or peculiar to specific local government areas, based on the type of vehicles that are involved. This reveals that the knowledge levels of road users vary with the type of vehicle they are using. This explained why some types of accidents are more frequent in some locations than others, as safety awareness levels increase with an increase in knowledge of road usage education. This data was used to create thematic maps aimed to drive home the prevailing safety situation and consciousness in each of the Local government areas, using ArcGIS computer software.

Table 5. The types of Accidents in Ibadan city (Source: Police traffic department)

LGA	MC/MC	Car/MC	Car/Car	MC/Ped	Car/Ped.	Total
IBA N	26	20	16	19	14	95
IBA S\E	25	21	5	24	20	95
IBA N\W	26	20	4	19	26	95
IBA S\W	27	25	4	81	21	158
IBA N\E	32	13	5	25	20	95
Total	136	99	34	131	121	538

Motorcycle-to-Motorcycle Safety Consciousness Level

This refers to accidents that occurred between motorcycles on the street and city roads.

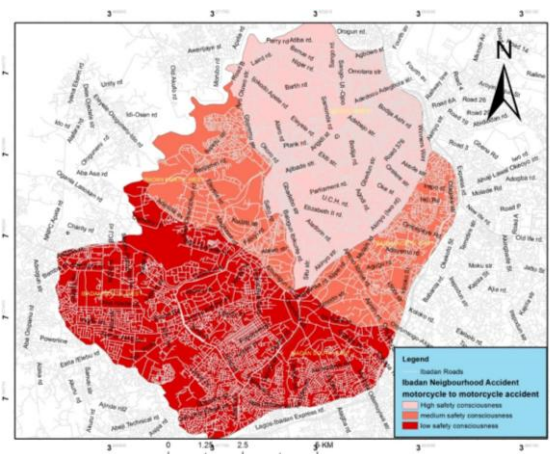


Figure 5. Map of Ibadan showing motorcycle-to-motorcycle safety consciousness levels.

The map in Figure 5 shows the level of safety consciousness among motorcycle users. It reveals that Ibadan South West and South East LGA are very low in safety consciousness level in terms of motorcycle usage. This mainly involves commercial motorcycle riders who do not go through proper training before they get on the road with the intention of making money. They are only conscious of who and where they will carry the next passenger. Another factor responsible could also be the smooth road in the locality, which promotes speed. The people mostly involved are students and workers who will not call their riders to order, either because they do not know or because they are too hasty to get to school or the workplace as soon as possible. These two local governments recorded motorcycle accidents, which means their awareness of motorcycle use is still very low, and so enlightenment and education on traffic laws and regulations will be needed to arrest the situation. Ibadan North is seen to be the most traffic safety conscious, followed by Ibadan North West and Ibadan North East.

Motorcycle-to-Pedestrians Safety Consciousness Levels

This refers to accidents that occurred between motorcycles and pedestrians on the street and city roads.

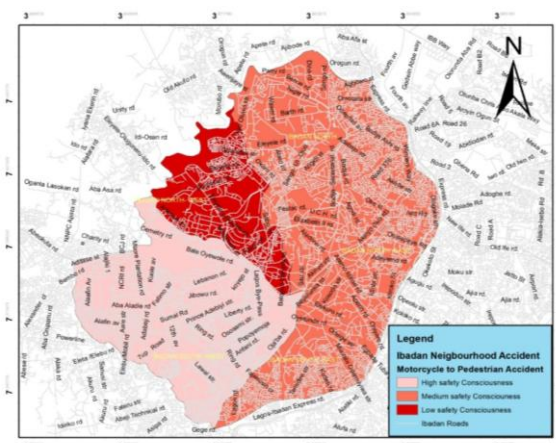


Figure 6. Map of Ibadan showing motorcycle-to-pedestrian safety consciousness levels.

The consciousness level in the use of the road between pedestrian and motorcycle users is seen to be very low in Ibadan North West LGA (see Figure 6). The streets here are relatively paved; there is more paved street in this LGA. It could be that the people here do not know how to cross the road, especially school children. Adults are also not left out, as adults are usually victims due to the carelessness and lack of respect for pedestrians on the part of motorcycle riders. Ibadan Southwest is observed to be the most safety-conscious LGA in terms of accidents involving pedestrians and motorcycles. It is also observed that the people here are educated, which may have influenced their road safety consciousness level. But the levels of consciousness in Ibadan North and Ibadan North East are medium.

Car-to-motorcycle safety consciousness levels

This refers to accidents that occurred between cars and motorcycles on the street and city roads.

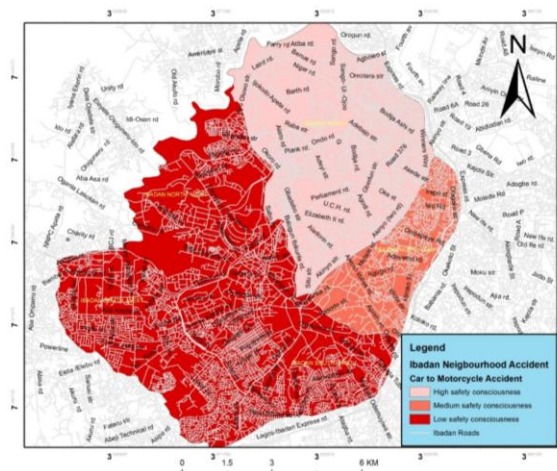


Figure 7. Map of Ibadan showing car-to-motorcycle safety consciousness levels.

Ibadan North West, Ibadan South West, and Ibadan South East local government areas are observed to have the highest reported accident cases between cars and motorcycles from the map in Figure 7. By implication, it can be said to have the lowest road safety consciousness level in terms of car-to-motorcycle accidents. This is associated with distraction on the part of car drivers due to the use of mobile phones during driving, mostly within the city, where there are no traffic officials to check them, bearing in mind the risky behavior of the average motorcycle rider. This act reduces driving performance in a number of ways, such as longer braking reaction time, reaction to traffic signals, and inability to keep in the correct lane, among others. Ibadan North has the highest consciousness level, followed by Ibadan North East.

Car-to-car safety consciousness levels

This refers to accidents that occurred between cars on the street and city roads.

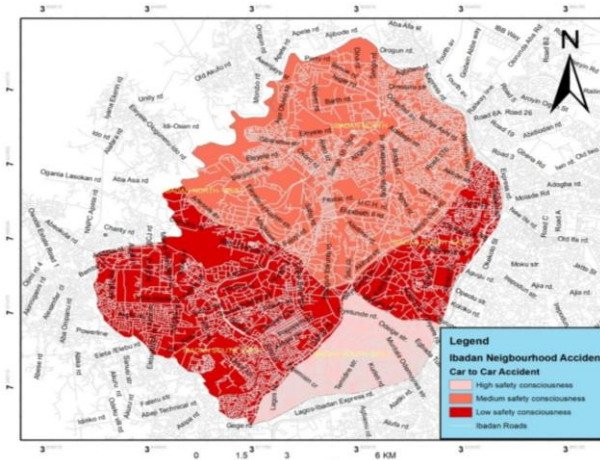


Figure 8. Map of Ibadan showing car-to-car safety consciousness levels.

The majority of drivers in Ibadan South West and Ibadan North East do not possess the right authorization from government-authorized agencies like the Federal Road Safety Commission, FRSC, and are unqualified to drive cars on the main road. This has made the safety level in the areas low.

This accounts for the high accident rate between cars; most drivers are ignorant of highway codes or traffic orders. They put their lives and those of other road users at risk of traffic accidents. As a result of their inexperience, since they were never given any tutorial or taught how to use vehicles on the road by government-accredited driving schools, their decision-making ability and reaction speed to traffic are bad. Ibadan North West and North East are moderate in their awareness levels, while Ibadan South East has the highest consciousness level (see Figure 8).

Car-to-Pedestrian Safety Consciousness Levels

This refers to accidents that occurred between cars and pedestrians on the street and city roads.

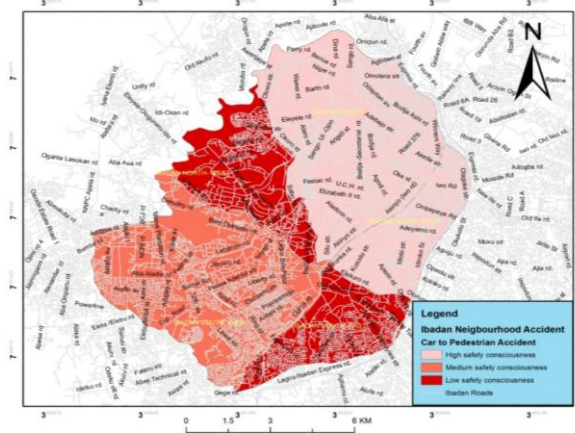


Figure 9. Map of Ibadan showing car-to-pedestrian safety consciousness levels.

Ibadan South East and North West are known for a high level of cars knocking people down. As observed, many roads in this LGA are paved, but there are no pedestrian footbridges. Where safety consciousness is high, people would have requested the construction of footbridges. But in Ibadan North and North East, footbridges or zebra crossings are made available to ensure the safety of the people, and if they use them, we can then say that the road safety consciousness level is very high, whereas in Ibadan South West, the safety consciousness level is at a medium level (see Figure 9).

Trends of accidents across the study area

Trend analysis refers to the general direction of movement to which the overall accident situation is trending across the city. The trend tool is available in the Spatial Analysis toolbox in ArcGIS. A critical look reveals that the general movement of accidents across the city is from west to east. From the map in Figure 10, areas with very low accident occurrence are shifting from the west of the city to the east, implying that as you move eastward, accident occurrence increases. It further shows that attention must be given to the two LGAs that are located in the Eastern part of Ibadan city, which are Ibadan South East and Ibadan North East, as a proactive measure to manage accident cases, which include education, enforcement, and road maintenance, to reverse this trend.

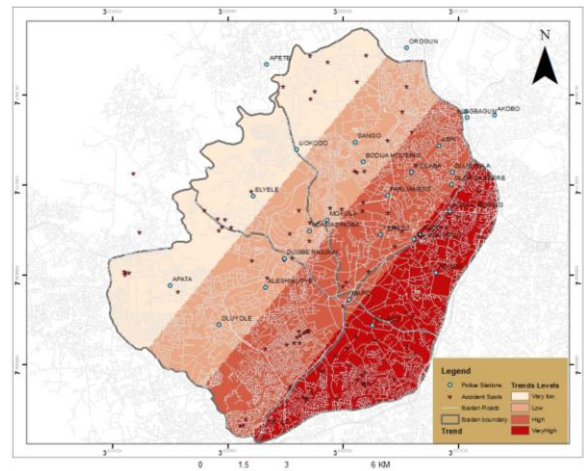


Figure 10. Ibadan city map showing the trend of accidents.

Accident incidences are observed to have a clustered distribution pattern across the city, while each LGA in the city has a dominant type of traffic accident associated with it. It was also seen that the movement direction of accidents across the city is West to East, as the number of traffic accidents increases as one moves further away from the police station or post.

The General Safety Consciousness Level

The map in Figure 11 shows the general road safety consciousness level. It is the combination of all the various types of accidents in the city, with the aim to know which of the local governments within the city has the lowest level of safety consciousness, as such a local government will have the highest accident occurrence.

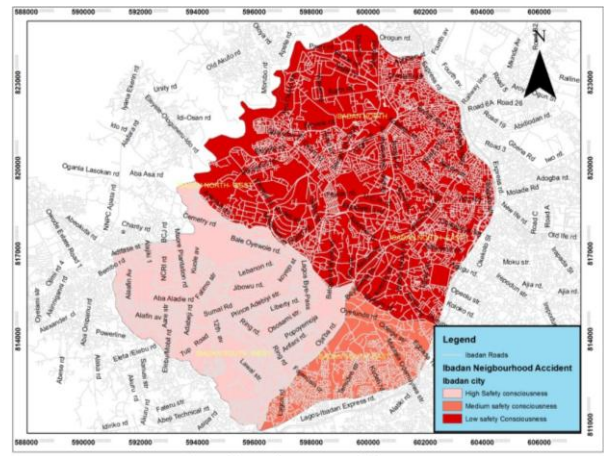


Figure 11. Map of Ibadan showing the general safety consciousness levels.

The map (Figure 11) shows the safety consciousness level of the entire Ibadan city as it concerns all the various categories of accidents. Ibadan South West is seen to have the lowest incidence of accidents when all occurrences are put together in the period under review. Ibadan South East is the next, while Ibadan North West, Ibadan North, and Ibadan North East are the worst, and by implication, the safety consciousness level in these LGAs needs to be improved upon so that the roads will be safe for use by all.

5. Factors Responsible for Road Traffic Crash Occurrences

Table 5 shows the causes of accidents in Ibadan city. As shown in Table 6, these causes are divided into three major factors. This includes driver-related factors, vehicle-related factors, and environmental factors. Each of the factors has contributed at different levels to accident occurrence in the study area.

Table 6. The factors responsible for accidents in the city. (Source: Police traffic department 2018-2023)

Factors	Magnitude of occurrence	Contribution %
Drivers related factors		
Over speeding	18	16.4%
Drink driving/drugs	11	10%
Distracted driving	10	9%
Inexperienced/unqualified drivers	20	18.2%
<i>Total</i>	<i>59</i>	<i>53.6%</i>
Vehicle-related factors		
Vehicle brake failure	15	13.6%
Vehicle tyres	12	11%
Vehicle light	10	9%
<i>Total</i>	<i>37</i>	<i>33.6%</i>
Environmental factors		
Bad roads/potholes	9	8.2%
Street trading	10	9%
Poor visibility	7	6.4%
<i>Total</i>	<i>26</i>	<i>23.6%</i>

5.1. Driver-Related Factors

The driver-related factors contributed 53.6% of the total accident occurrences within the period under review. The unsafe actions of the drivers that cause a traffic accident include:

Speed and indiscriminate use of Sirens

An increase in average speed is directly related both to the likelihood of a crash occurring and to the severity of the consequences of the crash. Traveling too fast for prevailing conditions or above the speed limit contributes to road traffic accidents. The risk of being injured increases exponentially with speed, much faster than the average speed. The severity of the accident depends on the vehicle speed change at impact and the transfer of kinetic energy. Though vehicles traveling slower than average speed are also at increased risk of road traffic accidents. From the data above, this unsafe act has happened 18 (eighteen) times, contributing 16.4% to accidents in the period under review. This action is mostly carried out by private or public office holders, such as bank vehicle drivers or government vehicle drivers.

Drink-driving and use of drugs

Drinking and driving increases both the risk of a traffic accident and the likelihood that death or serious injury will result. The risk of being involved in a traffic accident increases significantly above a blood alcohol concentration. Doctors often advise patients to abstain from driving vehicles or operating machinery while under certain drugs, as these drugs are known to cause side effects of sleepiness and fatigue. Accidents that occurred due to this action have hap-

pened 11 (eleven) times, contributing 10% to accidents in the period under review.

Distracted driving

There are many types of distractions that can lead to impaired driving, but recently, there has been a marked increase around the world in the use of mobile phones by drivers, which is becoming a growing concern for road safety. The distraction caused by mobile phones can impair driving performance in a number of ways, e.g., longer reaction times (notably braking reaction time, but also reaction to traffic signals), impaired ability to keep in the correct lane, and shorter following distances. Text messaging also results in considerably reduced driving performance, with young drivers at particular risk of the effects of distraction resulting from this use. Drivers using a mobile phone are approximately four times more likely to be involved in a traffic accident than when a driver does not use a phone. Hands-free phones are not much safer than hand-held phone sets, as they too have been recorded to result in traffic accidents when shocking news is received while driving. This unsafe act has caused accident situations 10 (ten) times, contributing 9% to accidents in the period under review.

Inexperienced and unqualified drivers

The majority of drivers do not possess the right authorization from government-authorized agencies like the Federal Road Safety Commission, FRSC, and are unqualified before driving cars or any other vehicle on road pavements. This is the major reason most drivers are ignorant of highway codes or traffic signs and symbols. They put their lives and those of other road users at risk of traffic accidents. As a result of their inexperience, since they were never given any tutorial or taught how to use their vehicles on highways by government accredited driving schools, their decision making ability and reaction speed to traffic is bad. Ibadan city has experienced accidents that result from inexperience 20 (twenty) times, or contributing 18.2% to accidents during the period under review.

5.2. Vehicle Factors

This factor has contributed 33.6% of the total accidents in the city during the period under review. The vehicle itself is a key factor when analyzing the remote causes of a traffic accident, and it is incorporated with gadgets like the horn, side mirrors, wipers, braking system, trafficators, headlights, and brake-lights (to mention just a few) so as to avoid road accidents. Malfunction of any vehicle parts, such as tires, engines, braking systems, or the lighting systems, can cause road traffic accidents. The reliability of the vehicle is in itself a function of the condition of the vehicle at every given time. Vehicle components and vehicle maintenance are the two main conditions that affect vehicle factors as they relate to the causes of road traffic accidents. Some of the unsafe conditions of vehicles include:

Vehicle Brake System

Brakes are generally applied to rotating axles or wheels. Vehicles use a combination of braking mechanisms that work

jointly with the accelerator as the main synchronizer of the speeds of vehicles. Any malfunctioning of the brake sub-system should be taken very seriously as a potential source of an unavoidable accident. Available data shows that a brake failure resulting in a traffic accident has occurred 15 (fifteen) times, contributing 13.6% to accidents in the period under review.

Vehicle Body and Tyres

The firmness of the structure of a vehicle, though less prominent, contributes to some measure to causing road traffic accidents. One of the dominant factors in determining the stability and safety of vehicles on the road is the tyres. Tyres designed and specified for cold regions are not those specified for temperate regions like Nigeria. However, this is not the case with most tyres used in Nigeria, as vehicle owners do not take the specification of tires into consideration when buying and fixing tyres onto their vehicles, and this has been known to cause tyre ruptures, thus leading to traffic accidents. Some other tyre-related causes of road accidents could be due to one or a combination of over-inflated tyres, under-inflated tyres, thread of tyres are thoroughly worn out. Accidents involving vehicles have occurred 12 (twelve) times, contributing 11% to the accident situation.

Vehicle Lights

The failure of vehicle lights is a major factor in road traffic accidents. Failure of vehicle lights has a tendency to misinform and mislead other road users, thereby providing a good opportunity for an accident to occur. Vehicle lights are very useful at all times during the day, in the dark, and in poor/bad weather. For example, a failed trafficator light of a vehicle ahead will not normally provide the usual warning to other vehicles behind that it is about to undertake a turning manoeuvre, and if for instance, the driver of the vehicle behind has not allowed for a sufficient stopping sight distance or the vehicle has a faulty brake sub-system, this could result in an accident occurring. These poor conditions of vehicles have produced 10 (ten) or contributing 9% of the reported accident cases in the city.

5.3. Environmental Factors

Environmentally related conditions, such as fog, sunrays, mist, and rain, in no small measure, contribute greatly to the rate of road traffic accidents. A poorly maintained vehicle, for example, on a rainy day, is most likely to cause a road traffic accident if the wipers are faulty and not functioning, as the driver will be unable to see ahead. Hence, environmental factors contributed 23.6% of the total accidents that occurred in the city in the period under review.

Accidents due to poor visibility occurred 7 (seven) times, contributing 6.4% to accidents. Our roads are often poorly designed, necessary important road facilities like drains are not adequately provided for, and to top it all off, they are rarely rehabilitated and are in a dilapidated state.

Poor condition of the roads, the city has experienced 9 (nine) times, contributing 8.2% to accidents due to this poor condition of the roads.

Street trading is another serious environmental condition that results in accidents in the city as vehicle drivers try to avoid people. The city has seen 10 (ten) times, or contributing 9% to accidents of this type.

6. Conclusions

In conclusion, a hypothesis test is aimed at determining whether there is a relationship between the Level of Traffic Education awareness and Road Accident Occurrences. Stated as thus:

H₀: There is no significant relationship between the level of traffic education awareness and usage and road accident occurrences.

H₁: There is a significant relationship between the level of traffic education awareness and usage and road accident occurrences.

Table 2 shows the number of accidents that have occurred in the study area within the period under review as obtained from the police traffic records, and Table 1 responds to the questionnaire, where respondents answered YES or NO to traffic and regulation as a way to test their level of safety awareness and compliance with traffic regulations. The “YES” percentages were rated against the “NO” percentages. It was entered into the SPSS (17.0) environment. The rating for each of the areas or zones was taken as X, while the number of accidents in each of the areas or zones was given by the police traffic department and was taken as Y; correlation analysis was carried out on the data. The results are presented in Table 7.

Table 7. The result of the correlation analysis

	Sign Ratings (%)	No. of Accident
Sign Ratings (%)		
Pearson Correlation	1	0.827
Sig. (2-tailed)		0.000
N	20	20
No. of Accident		
Pearson Correlation	0.827	1
Sig. (2-tailed)	0.000	
N	20	20

Table 7 presents the results of the correlation analysis. The calculated r was 0.827; p-values were < .01. This indicates a strong correlation between accident occurrences and the level of awareness of road signs and symbols. 0.827 indicates that the high safety of road users is greatly dependent on the level of awareness of road sign usage, and this, however, leads to a reduction in the occurrence of road accidents in the city. This, therefore, implies that there is a noticeable reduction in accident occurrences as road safety awareness and usage consciousness increase. We therefore accept the alternate hypothesis that states there is a significant relationship between the level of traffic education awareness and usage and road accident occurrences.

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Potential Effects of the 1 July 2026 Extension of Driving Time and Rest Period Rules to 2.5 – 3.5 t Vehicles in International Road Freight Transport

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Abstract This article analyses the potential effects of extending, from 1 July 2026, the obligation to use tachographs and to comply with regulations on driving time, breaks and rest periods to vehicles with a maximum permissible mass exceeding 2.5 t but not exceeding 3.5 t in international commercial road transport of goods. The aim of the study was to estimate the impact of these changes on the operation of enterprises in the transport, forwarding and logistics (TSL) sector. A mixed-method approach was applied, including a legal framework analysis, a comparison of transport time for two international routes under different vehicle categories and driver crew configurations (activity sequence diagrams), and an anonymous survey among representatives of transport and forwarding companies. The route analysis indicates that following the introduction of the regulations the time advantage of transport performed by vehicles with a maximum permissible mass ≤ 3.5 t in time-sensitive operations is significantly reduced, while the shortest transport time on the long-distance route is ensured by the double-crew configuration of a heavy goods vehicle. The survey results confirm an expected decrease in the competitiveness of transport operations performed using vehicles with a maximum permissible mass ≤ 3.5 t and indicate planned adaptation measures, in particular shifting part of the orders to vehicles with a maximum permissible mass > 3.5 t.

Keywords road transport, tachograph, driver working time, vehicles ≤ 3.5 t, mobility Package, transport time analysis, survey research

JEL R41, R48, K23

1. Introduction

International road freight transport in the European Union has undergone significant regulatory changes in recent years. One of the key reforms is the extension of the obligation to use tachographs and to comply with driving time, breaks and rest period regulations to vehicles used in international road transport of goods with a maximum permissible gross vehicle weight exceeding 2.5 tonnes but not exceeding 3.5 t, effective from 1 July 2026 [1]. Until the entry into force of these provisions, vehicles with a gross vehicle weight not exceeding 3.5 t have not been subject at the EU level to the regulations governing drivers' driving time and rest periods. In practice, international transport performed by light commercial vehicles (LCVs) has therefore relied on national rules of individual Member States (e.g., German FPersV with the requirement to maintain a *Kontrollbuch*). In many EU countries, such rules are weakly enforced, which often leads to their omission in practice [8]. As a result, the absence of tachograph obligations and limited inspection coverage may contribute to insufficient supervision of driving time, breaks and rest periods, with potential implications for road safety. This issue was already highlighted in Regulation (EC) No

561/2006 and, together with the objective of ensuring fair competition, constitutes an important rationale for the changes effective from 1 July 2026 [3]. Enforcement and cross-border cooperation aspects have also been addressed by the European Labour Authority (ELA) [7]. Previous research on working time regulations has primarily focused on heavy goods vehicles (HGVs), while the segment of LCVs (not exceeding 3.5 t) has remained underexplored in the context of international operations [4], [5]. Available studies indicate that transport companies are not fully prepared for the implementation of the new requirements [2]. The extension of driving time regulations and tachograph obligations to vehicles with a maximum permissible mass of 2.5-3.5 t may alter competitive conditions between LCVs and HGVs and influence transport organisation and operational decisions.

The aim of this article is to present the perspective of enterprises operating in the transport and forwarding sector regarding the planned regulatory extension effective from 1 July 2026, based on a survey conducted among representatives of transport and forwarding companies. In addition, the article compares the theoretical transport time for two international routes in different vehicle categories and single-driver / double-crew configurations, and analyses

enterprises' declarations concerning expected impacts on the number of routes performed, the competitiveness of LCVs and planned adaptation measures.

2. Methodology

2.1. Legal Framework and Scope of Analysis

The assumptions adopted in this study are based on the legal provisions regulating driving time, breaks and rest periods, as well as the obligation to use tachographs in road freight transport within the European Union, with particular emphasis on the extension of these regulations to vehicles with a maximum permissible mass exceeding 2.5 t but not exceeding 3.5 t in international transport from 1 July 2026. The analysis considers the following legal acts: Regulation (EC) No 561/2006 and its amendments [3], Regulation (EU) 2020/1054 [1], Regulation (EU) No 165/2014 [11], the AETR Agreement [12], and Directive 2002/15/EC [6]. The study focuses on driving time limits, mandatory breaks and daily rest periods, while weekly rest periods were excluded from the scope of the modelling due to the operational horizon of the analyzed routes.

2.2. Analysis of International Route Performance

The analysis of transport time was conducted for two economically significant international routes (Warsaw–Bologna and Strykow–Hamburg), selected based on the report of the Polish Road Transport Institute (PITD) [9]. A constant average speed of 90 km/h was assumed for both vehicle categories (≤ 3.5 t and > 3.5 t) in order to isolate the regulatory effect from technical and operational variability. This value corresponds to the midpoint of reported average motorway speeds. The analysis included three organizational variants:

1. vehicle > 3.5 t – single-driver configuration;
2. vehicle > 3.5 t – double-crew configuration;
3. vehicle ≤ 3.5 t – single-driver configuration (reflecting the legal situation before and after 1 July 2026).

The results are presented in the form of activity sequence diagrams illustrating driving periods, breaks and daily rest periods for each scenario.

2.3. Survey Research

The survey was conducted anonymously and addressed to a defined group of respondents from the transport and forwarding sector. Responses were requested from company owners (in the case of small enterprises), department managers, and specialists responsible for transport organisation. The sample selection included individuals possessing practical knowledge and direct influence on operational decisions within transport companies. Participation was voluntary, and respondents were informed about the research character of the questionnaire. The questionnaire included single- and multiple-choice questions as well as questions based on a five-point Likert scale. The

use of various question types enabled the collection of data concerning the company profile and fleet structure, as well as respondents' assessments related to the planned regulatory changes. The survey consisted of nine questions concerning the company's business profile, possession of LCVs (maximum permissible mass not exceeding 3.5 t) and, where applicable, the size of such a fleet, as well as the reasons for discontinuing the use of this vehicle category. The questionnaire also included questions regarding the level of awareness of the planned regulatory changes effective from 1 July 2026, the assessment of their impact on company operations, the expected influence on the number of transport routes performed, the perceived impact of working time restrictions on the competitiveness of LCVs, and planned adaptation measures in response to the new regulations.

3. Results

3.1. Analysis of International Route Performance

The analysis was conducted for two international routes (Warsaw, PL – Bologna, IT and Strykow, PL – Hamburg, DE) with reference to two vehicle categories: vehicles with a maximum permissible mass > 3.5 t and vehicles with a maximum permissible mass ≤ 3.5 t, as well as crew configurations (single-driver and double-crew for vehicles with a maximum permissible mass > 3.5 t). The results are presented in the form of activity sequence diagrams covering driving periods, mandatory breaks and daily rest periods. For vehicles with a maximum permissible mass ≤ 3.5 t, separate sequences were not presented for the legal situation after 1 July 2026, since, under the assumed identical average speed and the application of the same driving time, break and rest restrictions, the schedule is identical to the single-driver configuration for vehicles with a maximum permissible mass > 3.5 t (Figure 1). The double-crew variant for vehicles with a maximum permissible mass ≤ 3.5 t was not analysed for the same reasons.

Warsaw, PL - Bologna, IT route (1413 km)

Figure 1 presents the sequence of driving periods for a vehicle with a maximum permissible mass > 3.5 t in a single-driver configuration. The activities include driving periods, mandatory breaks (2×45 min) and a daily rest period (11 h 00 min). The total transport time amounts to 28 h 12 min, including driving time of 15 h 42 min, breaks of 1 h 30 min, and a daily rest period of 11 h 00 min.



Figure 1. Sequence of driving periods, mandatory breaks and daily rest period – Warsaw, PL – Bologna, IT route, vehicle with a maximum permissible mass > 3.5 t, single-driver configuration. Source: own elaboration.

Figure 2 presents the sequence of activities performed during transport by a vehicle with a maximum permissible mass > 3.5 t in a double-crew configuration. In this variant, alternating driving and availability periods were applied, which made it possible to complete the journey without introducing a stop resulting from the daily rest period within the analysed time horizon. In this configuration, the availability period of one driver occurs in parallel with the driving period of the other; therefore, the schedule does not distinguish an additional 45 min break as a separate activity. The total transport time amounts to 15 h 42 min.

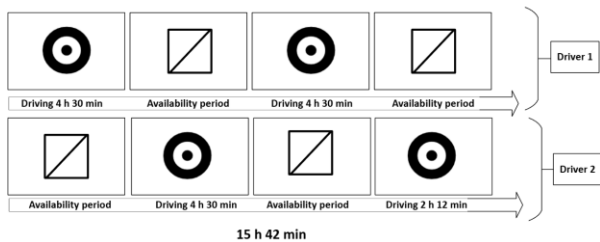


Figure 2. Sequence of driving periods and availability periods – Warsaw, PL – Bologna, IT route, vehicle with a maximum permissible mass > 3.5 t, double-crew configuration (Driver 1 / Driver 2). Source: own elaboration.

Figure 3 presents the sequence of activities for a vehicle with a maximum permissible mass ≤ 3.5 t in a single-driver configuration. The variant includes one mandatory break (45 min) and a daily rest period (8 h 00 min). The total transport time amounts to 24 h 27 min, including driving time of 15 h 42 min, a break of 45 min, and a daily rest period of 8 h 00 min. In the case of vehicles with a maximum permissible mass ≤ 3.5 t, the daily rest period has a conventional character (it does not result from the obligation to apply Regulation 561/2006 under the legal situation prior to 1 July 2026). In the analysis, a daily rest period of 8 h 00 min was adopted as a minimum organisational stop.

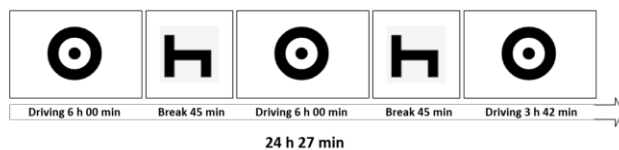


Figure 3. Sequence of driving periods, mandatory break and daily rest period – Warsaw, PL – Bologna, IT route, vehicle with a maximum permissible mass ≤ 3.5 t, single-driver configuration under the current legal framework. Source: own elaboration.

Strykow, PL –Hamburg, DE route (745 km)

Figure 4 presents the sequence of activities for a vehicle with a maximum permissible mass > 3.5 t in a single-driver configuration. The variant includes one mandatory break (45 min). The total transport time amounts to 9 h 02 min, including driving time of 8 h 17 min and a break of 45 min.

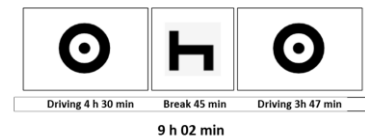


Figure 4. Sequence of driving periods and mandatory break – Strykow, PL – Hamburg, DE route, vehicle with a maximum permissible mass > 3.5 t, single-driver configuration. Source: own elaboration.

Figure 5 presents the sequence of activities during the Strykow, PL – Hamburg, DE route for a vehicle with a maximum permissible mass > 3.5 t in a double-crew configuration. In this variant, the availability period of one driver occurs in parallel with the driving period of the other; therefore, the schedule does not distinguish an additional 45 min break as a separate activity. The total transport time amounts to 8 h 17 min.

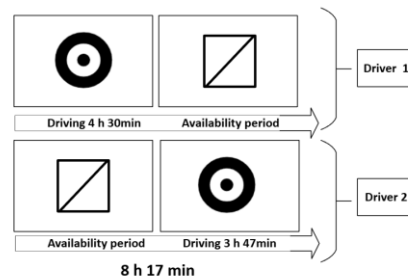


Figure 5. Sequence of driving periods and availability periods – Strykow, PL – Hamburg, DE route, vehicle with a maximum permissible mass > 3.5 t, double-crew configuration (Driver 1 / Driver 2). Source: own elaboration.

Figure 6 presents the sequence of activities performed by a vehicle with a maximum permissible mass ≤ 3.5 t in a single-driver configuration. Under the adopted assumptions, the driving time is identical to the variant for heavy goods vehicles and includes one break (45 min). The total transport time amounts to 9 h 02 min.

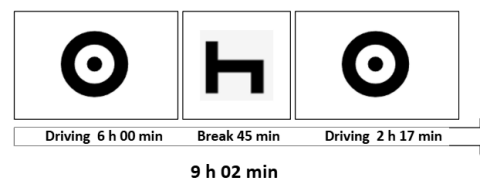


Figure 6. Sequence of driving periods and mandatory break - Strykow, PL – Hamburg, DE route, vehicle with a maximum permissible mass ≤ 3.5 t, single-driver configuration. Source: own elaboration.

The analysis of activity sequences indicates that on long-distance routes the shortest transport time is ensured by the double-crew configuration of vehicles with a maximum permissible mass > 3.5 t, compared to the single-driver configuration. Under the legal situation prior to 1 July 2026, the transport variant using vehicles with a maximum permissible mass ≤ 3.5 t is characterized by a shorter transport time in international operations, resulting from greater organizational flexibility. After the entry into force of the regulations on 1 July 2026, the time advantage of the transport variant using vehicles with a maximum permissible

2.5 – 3.5 t in international operations will be significantly reduced.

3.2. Survey Results

The survey covered 54 enterprises operating in the transport and forwarding sector.

In response to the question regarding the company’s business profile, 92.6% of respondents (n = 50) declared that they conduct international transport operations, while 24.1% (n = 13) indicated domestic transport. The question allowed multiple answers, which means that some enterprises conduct both domestic and international transport simultaneously.

Figure 7 presents the percentage distribution of responses to Question 2 concerning the possession of vehicles with a maximum permissible mass ≤ 3.5 t. The results indicate that the majority of surveyed enterprises declared the use of this vehicle category, while the remaining entities reported either not possessing such vehicles or having discontinued their use in the past.

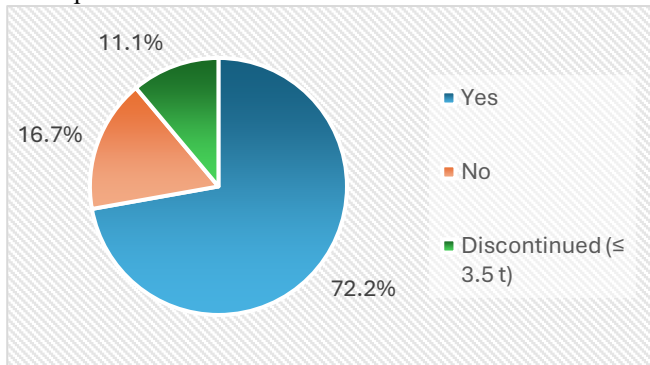


Figure 7. Possession of vehicles with a maximum permissible mass ≤ 3.5 t (n = 54). Source: own elaboration.

The fleet size structure in the surveyed group of enterprises is presented in Figure 8. The smallest fleet category was indicated most frequently, while the remaining responses included medium and large fleets. Responses were provided exclusively by respondents who, in the previous question, declared the possession of this vehicle category.

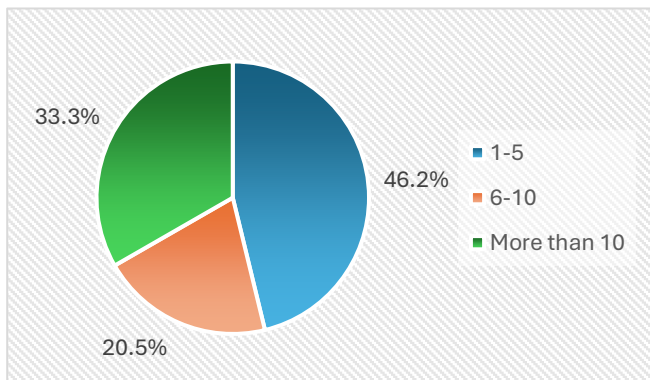
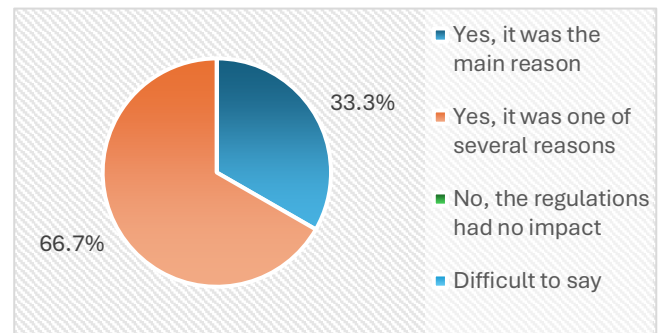


Figure 8. Fleet size of vehicles with a maximum permissible mass ≤ 3.5 t (n = 39). Source: own elaboration.

In the surveyed group of enterprises that discontinued the use of vehicles with a maximum permissible mass ≤ 3.5 t, the planned regulatory changes were indicated as a significant reason for this decision. As illustrated in Figure 9, for some respondents they constituted the main reason for discontinuation, while for others they represented one of several reasons. The responses concerned exclusively



entities that had discontinued the use of this vehicle category.

Figure 9. Impact of regulatory changes on the discontinuation of vehicles with a maximum permissible mass ≤ 3.5 t (n = 6). Source: own elaboration.

The survey results indicate a high level of respondent awareness regarding the planned regulatory changes effective from 1 July 2026 in international road transport. In response to the question concerning awareness of the planned changes, 94.4% of respondents (n = 54) declared familiarity with the introduced regulations. Only 3.7% indicated the answer “partially”, while 1.9% reported no knowledge in this area.

Respondents assessed the impact of the planned regulatory changes on company operations on a five-point scale (1 – very negative impact, 5 – very positive impact) (n = 54). The most frequently indicated rating was 3 (35.2%, n = 19). Ratings 1 and 2 each accounted for 25.9% of responses (n = 14 each), which means that, in total, ratings in the range 1 – 3 represented 87.0% of all responses (n = 47). Positive ratings were less frequent: 4 (7.4%, n = 4) and 5 (5.6%, n = 3). The distribution of responses indicates a predominance of neutral and negative assessments, with a limited share of positive evaluations.

Most respondents anticipate changes in the number of transport routes performed following the entry into force of the new regulations. An expected impact on the number of routes was indicated by 74.1% of respondents (n = 40), while 16.7% (n = 9) stated that an impact is possible but difficult to assess unequivocally at the time of the survey. No expected impact was declared by 9.3% (n = 5). These results indicate that a clear majority of enterprises expect changes in the number of routes performed as a consequence of the new regulations.

Respondents most frequently indicated a deterioration in the competitiveness of transport operations performed using vehicles with a maximum permissible mass ≤ 3.5 t as a result of the introduction of new requirements related to driving time limits, mandatory breaks and daily rest periods. A summary of responses is presented in Figure 11. The most commonly expressed concerns related to the loss of the time

advantage and a decrease in the profitability of this transport segment. These results refer to respondents' declarations regarding the expected impact of the planned regulations on the competitiveness of transport operations performed by vehicles with a maximum permissible mass ≤ 3.5 t.

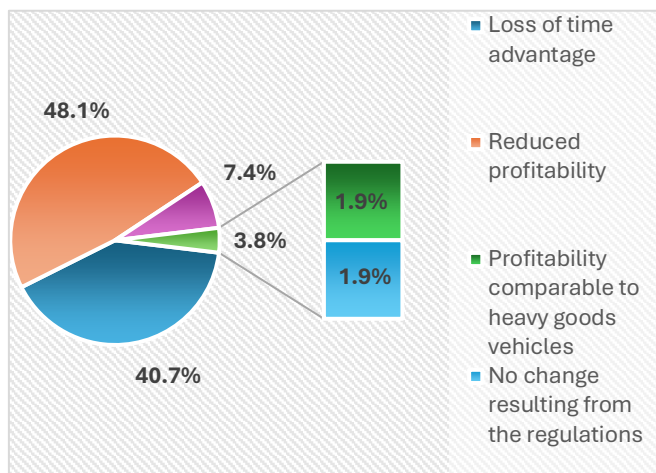


Figure 11. Impact of driving time restrictions on the competitiveness of transport operations performed using vehicles with a maximum permissible mass ≤ 3.5 t (n = 54). Source: own elaboration.

In the context of the planned regulatory changes, enterprises declared diversified directions of operational adaptations. The most frequently indicated measure was shifting orders to vehicles with a maximum permissible mass > 3.5 t (43.1%, n = 22). Another commonly selected response was a change in the service profile (19.6%, n = 10). Some respondents also indicated business closure (15.7%, n = 8) and establishing cooperation with large forwarding companies (13.7%, n = 7). In 9.8% of cases (n = 5), responses were classified as unspecified (no clarification provided). The remaining responses were single indications (2.0%, n = 1 each) and included, among others, no planned actions, not possessing vehicles in this category, waiting for the market response, and the answer "I do not know".

The results obtained from the survey indicate a high level of enterprise awareness regarding the planned regulatory changes. Most respondents anticipate that the new regulations will affect the number of transport routes performed and the competitiveness of transport operations carried out using vehicles with a maximum permissible mass ≤ 3.5 t. The most frequently declared adaptation measure is shifting part of the orders to vehicles with a maximum permissible mass > 3.5 t.

4. Conclusions

In this article, an assessment was conducted of the potential effects of subjecting vehicles used in international commercial road transport of goods to regulations concerning tachographs and driver working time, which will enter into force on 1 July 2026 [1]. The results of the transport time analysis indicate that, once light commercial vehicles are covered by break and rest requirements, the time

advantage of the transport variant performed using vehicles with a maximum permissible mass ≤ 3.5 t in international operations will be significantly reduced. On long-distance routes, the shortest transport time is ensured by the double-crew configuration of vehicles with a maximum permissible mass > 3.5 t; however, this is associated with higher costs and additional staffing requirements. The previous organisational flexibility of transport operations performed using vehicles with a maximum permissible mass ≤ 3.5 t, resulting from less restrictive working time constraints, remains a key factor supporting their use in time-sensitive transport.

A limitation of the calculations performed is the assumption of a constant average travel speed and the omission of the effects of congestion and transshipment operations. The survey results confirm that enterprises anticipate significant changes in transport organisation, including a decrease in the number of transport routes performed and a reduction in the competitiveness of transport operations carried out using vehicles with a maximum permissible mass ≤ 3.5 t. Respondents most frequently indicated the loss of time advantage and a decrease in the profitability of operating vehicles in this category in international transport, and some companies had already discontinued their use earlier, referring to regulatory factors. Among the planned adaptation measures, shifting orders to heavy goods vehicles predominated. The obtained results suggest that after 1 July 2026 the use of vehicles with a maximum permissible mass ≤ 3.5 t in time-sensitive international transport may become limited, while their importance in urban distribution and last-mile deliveries is likely to be maintained. From a practical perspective, this may imply the need to modify supply chain planning, including, among other measures, increasing safety stock levels.

4.1. Possible Directions of Enterprise Adaptation and Market Implications

The planned actions declared by respondents, in particular the shifting of part of the orders to vehicles with a maximum permissible mass > 3.5 t, indicate the possibility of transferring part of the demand from the light vehicle segment to the heavy vehicle segment. This direction is consistent with the results of the activity sequence analysis, which show that once vehicles with a maximum permissible mass of 2.5–3.5 t are covered by the regulations effective from 1 July 2026, the previously shorter transport time achieved using this vehicle category (particularly in time-sensitive transport operations) will be significantly reduced.

In practice, this may result in a reduced role of vehicles with a maximum permissible mass ≤ 3.5 t in international transport requiring high temporal flexibility, especially in urgent and short-term operations. Consequently, enterprises may more frequently use organisational solutions such as a double-crew configuration in heavy goods transport or the reorganisation of schedules (e.g., staging of transport

operations, increasing the number of transshipment operations) [5].

From a broader perspective, the reduction of time flexibility in certain international relations may influence supply chain planning practices, particularly in Just in Time systems, leading to greater importance of time buffers and/or safety stock. This direction is consistent with the shift observed after supply chain disruptions during the COVID-19 pandemic towards strategies referred to as Just in Case [10]. The scope and pace of these changes will depend on the scale of regulatory enforcement, the availability of drivers, and the costs associated with organising a double-crew configuration.

4.2. Study Limitations and Further Research Directions

Further research should consider a broader set of routes and operational scenarios, as well as a more in-depth cost analysis, including labour costs, fleet and driver maintenance costs, freight costs in relation to the volume of goods transported, and the risk of delays, in order to assess more comprehensively the effects of the upcoming regulatory changes. The analysis should also cover the organisational structure of manufacturing enterprises and the changes that occurred following the introduction of the regulations, in the context of planning in Just in Time systems and a shift towards local supplier markets.

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A New Operating Model for Single Wagonload Transport: From Train Formation to Integrated Customer Service

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Abstract Single wagonload transport is one of the most complex production systems in rail freight transport. Its technological complexity results from the combination of local service, marshalling, shunting, long-distance haulage and subsequent wagon distribution to final customers. The aim of this paper is to propose a technological framework for the revitalisation of single wagonload transport in Slovakia, focusing on three key areas: time-organised train formation based on the overnight production cycle, the definition of a core network of train-formation and service nodes, and the separate organisation of the first and last mile. The paper builds on available data on the development of single wagonload transport in Slovakia, the European Union study on Single Wagonload Traffic and the technological principles of train formation. The result is an operating model combining the concentration of train formation in decisive nodes, regular overnight relations, regional collection and distribution links, digital information about wagon consignments and selective support for service points. The proposed model may serve as a professional basis for further discussion on maintaining and modernising single wagonload transport as part of sustainable rail freight transport.

Keywords single wagonload transport, train formation, overnight production cycle, marshalling yard, first mile, last mile, rail freight transport

JEL L92, R41, R48

1. Introduction

Single wagonload transport belongs to the traditional, yet also most demanding, products of rail freight transport. Its importance lies in the fact that it allows customers who do not have sufficient freight volumes to form a block train to be connected to the railway network. As a result, rail is not limited to large industrial and terminal flows but can also serve dispersed regional and industrial consignments [1].

In European terminology, this segment is referred to as Single Wagonload Traffic (SWL). The European Commission defines it as rail freight flows smaller than a full train, i.e. transport operations that are not carried out as a block train with the same train composition from origin to destination. According to the European Commission study, SWL represented a significant share of rail freight transport in the analysed countries, with an estimated volume of approximately 75 billion tonne-kilometres in 13 analysed countries and 80 to 85 billion tonne-kilometres in the EU and Switzerland [1].

Despite this significance, the single wagonload system has been under long-term pressure. The reason is its high technological and economic complexity. Compared with block trains, it requires considerably more shunting and train-formation operations, multiple handling of wagons, coordination between local and long-distance transport, more complex documentation and higher infrastructure requirements. In its business plans, Železničná spoločnosť Cargo Slovakia, a.s. (ZSSK CARGO) states that SWL is the most technologically and economically demanding transport system and that it ties up substantial technical and personnel capacities [2].

The significance of SWL cannot be assessed only through the business profitability of the operator. The European Commission regards SWL as an important part of rail freight transport, while also pointing to its structural problems: high costs of marshalling, shunting, distribution trains and the first/last mile. A Slovak study by the Ministry of Transport of the Slovak Republic further states that the current state of SWL transport, including the regulatory environment, is not sustainable in the long term in Slovakia and that the segment generates a negative financial result [1], [8], [9].

Discussion on the future of SWL therefore often focuses on public support. Such support is undoubtedly important, but it is not sufficient by itself. If support were provided without changing the technology, it would only extend the life of a costly system without substantially improving its quality and efficiency [8], [9], [12]. It is therefore necessary to search simultaneously for a technological model that reduces unnecessary handling interventions, accelerates wagon transfer through nodes, increases service predictability and better connects local service with long-distance haulage.

The aim of this paper is to propose a technological framework for the revitalisation of SWL in Slovakia. The focus is not on the financial support mechanism, but on the operating organisation of the system. The key elements are:

- time-discrete train formation based on the principle of the overnight production cycle;
- a core network of decisive train-formation and routing nodes;
- separately organized first and last mile;
- reduction in the number of wagon reclassifications;

- digitalization of consignment and wagon information;
- measurable service-quality indicators.

2. Technological Nature of Single Wagonload Transport

A single wagonload consignment is not merely a “small train”. It is an independent production system in which individual wagons or smaller wagon groups are gradually collected, sorted and assigned to relations according to their destination. From a technological point of view, it is a chain that may include several links: siding or loading point - local collection - regional node - train-formation station - line-haul relation - destination sorting - local delivery - consignee [4], [19].

Each link in this chain creates costs, time dependencies and a potential risk of delay. If local collection is delayed, the wagon will not be transferred to the long-distance relation. If the line-haul relation is delayed, the wagon may miss the morning sorting or delivery to the customer. If connections between trains are not sufficiently stable, the entire system loses predictability [4], [19], [20].

The fundamental difference between a block train and SWL is therefore the number of technological handling operations performed on the wagon. In a block train, the objective is to maintain the train set in a stable composition. In SWL, the objective is to integrate individual wagon flows into efficient train relations. Train formation is therefore the core of the whole system [4], [20].

The operating principles of train formation emphasise that moving each wagon separately would be inefficient. Wagons are therefore organised into train flows, and the train-formation plan determines the train-formation stations in which wagons are reclassified and collected and prescribes their routing [4], [7].

Under current conditions, however, optimising wagon routing alone is not sufficient. It is equally important to align train formation with customer time requirements, railway network capacity and the availability of local service [4], [19]. This is why the principle of the overnight production cycle is relevant for SWL revitalisation.

The current network of train-formation stations on the infrastructure of Železnice Slovenskej republiky (ŽSR) forms a two-level operating structure: basic marshalling yards as the main nodes of long-distance train formation and other train-formation stations as regional points of collection, distribution and local service. An overview of all train-formation stations and their classification is given in Table 1 [7].

From the point of view of freight transport technology, the current situation is characterised by the concentration of decisive long-distance train formation in a limited number of basic marshalling yards. Other train-formation stations primarily perform regional, routing or service functions in relation to their catchment areas, local loads and links to through relation trains. This model corresponds to the trend of concentrating train-formation work in a smaller number of important nodes, while the efficiency of the system depends on the quality of links between basic marshalling yards, other train-formation stations and intermediate stations served by local service trains [7].

Table 1. Train-Formation Stations of ŽSR [7].

Group	Number	Stations
Basic marshalling yards	6	Bratislava východ; Čierna nad Tisou; Košice; Štúrovo; Zvolen nákladná stanica; Žilina-Teplice
Other train-formation stations	27	Banská Bystrica; Bratislava ÚNS; Devínska Nová Ves; Galanta; Haniska pri Košiciach; Horná Štubňa; Komárno; Kúty; Lenartovec; Leopoldov; Levice; Lisková; Lučenec; Lužianky; Nováky; Nové Zámky; Plešivec; Podbrezová; Prievidza; Prešov; Spišská Nová Ves; Strážske; Trebišov; Trenčianska Teplá; Trnava; Tmovec nad Váhom; Zohor
Total train-formation stations	33	basic marshalling yards + other train-formation stations

From the perspective of single wagonload transport, it is important that relation trains are defined in the Train-Formation Plan as trains intended for the transport of relation loads, i.e. single wagon consignments, including empty wagons intended for loading. Through relation trains provide the transport of long-distance loads between train-formation stations, whereas local service trains provide the distribution of local loads to sidings, public loading and unloading tracks and intermediate stations. This system represents the capacity and technological backbone for single wagonload transport on the ŽSR network [7]. For further stabilisation of the SWL system, reliable time, capacity and technological links between these levels are essential, particularly in the form of connections between local service trains, through relation trains and basic marshalling yards.

It should be emphasised that ZSSK CARGO uses the technological time of wagon collection to achieve the loading norm, both in terms of train weight and train length. This makes it difficult to determine the delivery time of a wagon consignment with sufficient accuracy [2].

Performance and economic data confirm that the current SWL system is significantly smaller than in the past. In a broader operating sense, the volume of SWL decreased from 17.5 million tonnes in 2005 to approximately 6.3 million tonnes in 2021, while its share in the transport structure decreased from 36% to 13%. Within the definition of SWL support according to the ZSSK CARGO 2026 methodology, the volume decreased from 3.8 million tonnes in 2021 to 2.5 million tonnes in 2025 [3]. At the same time, the overall rail freight market measured in gross tonne-kilometres is declining, and the share of ZSSK CARGO in this market is decreasing. These data support the conclusion that SWL on the ŽSR network is no longer only a technological issue, but also a strategic question of maintaining rail service for dispersed industrial flows.

Table 2. Simplified Time Model of the Overnight Production Cycle [4], [19].

Phase	Time Period	Main Activity	Key Indicator
Daytime collection	D0, 8:00-16:00	Loading and preparation of wagons	readiness of wagon for collection
Evening collection	D0, 16:00-21:00	Movement to a regional or main node	compliance with wagon transfer time
Evening sorting	D0, 18:00-23:00	Sorting and formation of overnight trains	wagon dwell time in node
Overnight haulage	D0/D1, 22:00-5:00	Long-distance movement between nodes	compliance with night-time window
Morning sorting	D1, 4:00-7:00	Reclassification in the destination area	readiness for distribution
Daytime distribution	D1, 7:00-14:00	Delivery of wagons to consignee	delivery within guaranteed window

3. Overnight Production Cycle as a Technological Basis for SWL Organization

The overnight production cycle, often referred to in Central European operational practice as the “night jump”, is a way of organising wagon consignments in which the decisive long-distance haulage takes place at night. Its logic is based on a simple operational and commercial assumption: customers need to load and unload during the day, while rail can effectively use night-time capacity windows for the long-distance movement of wagons [4], [19], [21].

The basic overnight production cycle can be described as follows:

1. D0 - daytime wagon collection: wagons are loaded and collected during the day at local service points, such as sidings, loading points and public loading and unloading tracks.
2. D0 - afternoon and evening collection: wagons are moved to regional or main train-formation nodes.
3. D0/D1 - overnight main haulage: collected wagons are moved between main train-formation nodes in regular overnight relations operated according to a fixed time regime.
4. D1 - morning sorting: wagons are sorted in the destination area into directions.
5. D1 - daytime distribution: wagons are delivered by local service trains to consignee sidings or loading points.

This principle transforms train formation from a continuous and not always predictable system into a time-organised network. The customer can thus receive clearer information about the latest time at which the wagon must be ready for dispatch and when delivery can be expected. The railway undertaking and the infrastructure manager can better plan capacity windows, shunting locomotives, classification tracks and staff [19].

However, the overnight production cycle is not merely an issue of timetable. It is a complete production regime. It requires:

- fixed cut-off times for wagon submission and collection;
- stable evening and night departures between nodes, i.e. a fixed timetable for freight transport;
- sufficient capacity of train-formation stations;
- reliable morning sorting;
- connecting local and service trains;
- an information system for tracking wagon passage.

If any of these elements fail, the benefit of the overnight production cycle is lost. Therefore, this principle must be designed as an integrated operating model, not merely as a selection of night train paths in the timetable [19], [21].

4. Core Train-Formation Network

For the overnight production cycle to function, it must be based on a clearly defined network of nodes. Not every station can perform the same function. A technologically efficient SWL system requires a multi-level structure [4], [7]:

1. main train-formation and marshalling nodes;
2. regional routing nodes;
3. satellite service points;
4. sidings and public loading points.

Main nodes should provide long-distance routes and overnight relation trains. They should have sufficient capacity of track groups, technical equipment, staff and digital support [19], [21]. Their role is not to serve every customer directly, but to create the backbone of the network.

Regional nodes should collect wagons from their catchment areas and distribute wagons arriving from the main network. They do not need to have the full function of a large

marshalling yard, but they must be capable of efficiently organising service and local trains [4], [7].

Satellite points and siding form the capillary part of the system. Their existence determines whether rail can also reach small and medium-sized customers. If these points disappear, rail may remain strong in block trains, but it loses regional accessibility.

Historical development in Slovakia shows that the network of train-formation stations has been gradually rationalised. This trend is not incorrect, because concentrating train formation in more powerful nodes can reduce costs and increase quality. The problem arises when concentration is not accompanied by functional regional service. In that case the number of nodes decreases, but the accessibility of the service for customers also deteriorates [7].

The objective should therefore not be a mechanical restoration of all historical train-formation points. It is necessary to create a core network that combines concentration with accessibility.

Table 3. Functions of Nodes in the Proposed Core SWL Network [4], [7].

Network Level	Main Function	Typical Activities	Risk in Case of Absence
Main train-formation node	Long-distance routing and overnight haulage	marshaling, formation of relation trains, gateway links	loss of network coordination
Regional node	Collection and distribution of wagons	linking the catchment area, formation of wagon groups	extension of first/last mile
Satellite service point	Local service of the region	loading, unloading, local service trains	customers shifting to road transport
Siding/loading point	Direct customer interface	wagon placement and removal	loss of rail accessibility

5. First and Last Mile as a Critical Link

In discussions about rail freight transport, attention is often focused on the long-distance train run. In SWL, however, the decisive link is often the first and last mile. This is the phase in which the wagon enters the network from the customer and leaves the network back to the customer [1], [4].

First-mile and last-mile service is demanding because it:

- works with small volumes;
- requires shunting locomotives and staff;
- is spatially dispersed;
- often depends on a specific customer or siding;
- has lower productivity than line-haul operation;
- is sensitive to irregular orders.

If the first and last mile are not addressed separately, the SWL system cannot function. Even the best organised overnight network loses its significance if wagons do not reach the node from the siding in time or are not delivered from the node to the consignee [1], [4].

ZSSK CARGO states that SWL ties up high technical and personnel capacities and has a longer wagon cycle than block trains. It follows that optimisation must be focused precisely on those parts of the chain where capacities are tied up for the longest time and with the lowest productivity [2], [3].

Separate organisation of the first and last mile may take several forms:

- regional service contracts;
- a short-line or short-liner model;
- sharing of shunting capacities;
- service only in selected time windows;
- support for strategic sidings;
- linking SWL with regional terminals [6].

For Slovakia, a combined model is particularly appropriate. Some service points have strategic significance and should be included in the core network. Others may be served only when a minimum volume is reached or based on an individual calculation. Another group may be suitable for intermodal transformation [6].

6. Reducing the Number of Wagon Reclassifications

One of the most important technological indicators of SWL quality is the number of wagon reclassifications. Each reclassification means time, costs, risk of delay, the need for track capacity and shunting work [20]. The objective of a modern SWL model should therefore be to minimise the number of handling contacts with the wagon.

In simplified terms, three models can be distinguished:

- a traditional multi-stage model, in which a wagon passes through several routing and marshalling stations;
- a concentrated network model, in which wagons converge into main nodes and are subsequently routed by overnight relations;
- a hybrid model, in which strategic wagon flows remain in SWL and part of low-volume flows is transformed into intermodal transport.

For Slovak conditions, the second and third models are particularly suitable. The objective should be that most wagons in the core network pass through no more than one main train-formation node between the origin and destination regions [4], [20]. Ideally, the number of major marshaling interventions should be minimized to:

- regional concentration;

- main route;
- destination distribution.

If a wagon passes through too many nodes, the system loses competitiveness against road transport [1], [14], [20].

Table 4. Comparison of Technological SWL Models [1], [4], [20].

Model	Number of Reclassifications	Advantage	Disadvantage
Traditional multi-stage model	high	wide network accessibility	long times and high costs
Concentrated overnight model	medium	better predictability and higher productivity	higher dependence on main nodes
Hybrid SWL + intermodal model	selective	preservation of strategic flows and transformation of weak relations	higher requirements for decision-making and data

7. Digitalization as a Condition for Modern SWL

Technological revitalisation of SWL is not possible without digitalisation. Customers today expect simple service ordering, information on consignment position, estimated time of arrival and timely notification of deviations. If they do not receive this information, road transport or an intermodal operator is often more attractive [10], [18], [22].

Digitalisation in the SWL system should include:

- electronic consignment ordering;
- digital wagon status;
- wagon location tracking;
- information on connections;
- ETA prediction;
- electronic train documentation;
- connection to TAF TSI;
- service quality evaluation [10], [18].

In the future, Digital Automatic Coupling (DAC) may also play an important role. Its benefit for SWL may be greater than for block trains, because SWL is precisely the segment that involves frequent coupling, uncoupling and wagon sorting [10], [22]. DAC, however, cannot be regarded as a short-term solution. It is a strategic technology for which the system must gradually prepare [22].

In the short term, basic digital functions are more important: reliable data on wagons, consignments, arrivals, departures and connections. Without these data, the overnight production cycle cannot be managed effectively, and the quality of the core network cannot be evaluated [10], [18], [22].

8. Proposal of a Technological Model for Slovakia

Technological modernisation of SWL must be understood as a combination of organisational and digital measures. In European documents, DAC is presented as a tool for the digitalisation and automation of rail freight transport that can

Table 5. Key Indicators of Technological SWL Revitalization [17], [18].

Area	Indicator
Time	average time from wagon-consignment submission to delivery
Train formation	number of reclassifications per wagon
Nodes	average wagon dwell time in the train-formation station
Quality	share of wagons delivered within the guaranteed window
Capacity	utilization of routing and departure tracks of decisive train-formation stations
First/last mile	number of served loading and unloading points, including public loading/unloading tracks, sidings and loading points
Digitalization	share of consignments with available ETA
Efficiency	cost per wagon or wagon-kilometer
Externalities	estimated number of avoided truck journeys

support higher capacity and productivity [10], [22]. In SWL conditions, its importance is specific because this segment works with frequent wagon reclassification. Based on the previous sections, a framework technological model for revitalising SWL in Slovakia can be proposed. It should consist of six elements.

8.1. Definition of the Core Network

First, it is necessary to determine which nodes, relations, sidings and commodity groups should be part of the core SWL network. Decisions should be based on transport volume, strategic importance, availability of alternatives and social benefits [7], [8], [17].

8.2. Introduction of Regular Overnight Relations

Stable overnight relation trains with guaranteed time windows should be operated between the main nodes. These fixed-timetable relations should form the backbone of the system [19], [21].

8.3. Linking Regional Service with the Overnight Cycle

Local and service trains must be timed to connect to evening departures and morning arrivals of relation trains. Without this link, the overnight production cycle loses its significance [4], [19].

8.4. Separate Organization of First and Last Mile

The service of siding and loading points should be planned separately. Strategic points should be included in the supported network, while others should be addressed according to volume or through an alternative intermodal solution [6].

8.5. Digitalization of Information

Each wagon in the core SWL system should have a digital status: relation, planned train, connection, ETA, technical restrictions and documentation status [10], [18].

8.6. Quality Measurement

The system must be evaluated regularly. Without measurement, it is not possible to decide which parts of the network are efficient and which should be transformed [17].

9. Discussion

The proposed technological model does not assume a return to the historical extent of train formation. Such an approach would not be realistic or economically justifiable. The aim is to create a smaller, but more stable and higher-quality network [7], [12], [13]. This network would be capable of serving strategic wagon flows, while not maintaining inefficient relations without sufficient significance.

At the same time, it must be emphasised that technology alone is not sufficient. Without an economic support framework, especially for first/last-mile service, the system will remain under pressure. Public support should, however, be linked to technological reform. The state should not support an inefficient status quo, but a modernised service with clearly defined parameters [8], [9], [12].

Another issue is the relationship with intermodal transport. Intermodal transport should not be understood as a competitor to SWL, but as a complementary transformation layer. Some flows that are currently, or historically were, wagonload consignments may in future be more efficiently handled using containers, swap bodies or other units. Conversely, for specific industrial commodities, direct wagon placement will remain irreplaceable [1], [6].

The greatest risk is a passive scenario. If neither technologically modernised SWL nor an intermodal alternative is supported, dispersed flows will shift to road transport. This may reduce the problem for the rail freight operator, but it increases the burden on public infrastructure, emissions, safety and regional accessibility [14], [17].

Foreign practice shows that maintaining SWL requires a combination of support and reform. Austria supports selected forms of rail freight transport through the SGV-Plus programme, while Switzerland approaches SWL as an ordered basic network with multi-annual financing. For Slovakia, this implies that any support for SWL must be stable, transparent and linked to technological modernisation, rather than merely compensating losses [12], [13].

10. Conclusions

Single wagonload transport cannot be revitalised by financial support alone. Above all, it requires a new technological and organisational model. Its core should be time-organised train formation based on the overnight production cycle, a stable network of decisive nodes, separately organised first and last mile, and digitalisation of wagon and consignment information [4], [10], [19], [22].

Slovakia still can maintain the core of the SWL system, but only if it moves from passively maintaining the existing situation to active modernisation. This means less randomness, more regularity, fewer unnecessary reclassifications, better customer information and a clear distinction between strategic and transformable flows [3], [6].

The proposed model does not mean preserving all historical wagonload relations. It means preserving those that have technological, industrial and social justification. Other flows should be assessed in terms of their potential transition to intermodal transport.

The future of SWL therefore depends not only on whether the state is willing to support the system. It also depends on whether the rail sector can offer a modern, predictable and technologically efficient product. The overnight production cycle, the core network and high-quality first and last mile can form the basis of such a change [1], [4], [19].

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Structural Patterns and Multi-Path Development of China's Regional Digital Economy

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Abstract This research is about the structural characteristics and regional differences of digital economy development in 31 provinces of China from 2014 to 2021. The entropy weight-TOPSIS technique is used to identify the main reasons for regional differences in the digital economy through a four-dimensional evaluation framework of 20 variables. The results show a significant structural variation across regions. The basic sources of regional differentiation are the volume of telecommunication services, the turnover of the technology market, and the revenue from the software business, although indicators of digital finance are relatively modest. The East region has better industrial and innovation capability; the Central mainly depends on the communication-scale expansion; the West region focuses on the technological transformation; and the Northeast provides a hybrid infrastructure-technology framework. The results indicate that the development of China's digital economy has a multi-path structural feature, rather than a simple hierarchical structure.

Keywords Digital economy, Regional heterogeneity, Structural characteristics, Entropy-weighted TOPSIS, Regional development

JEL O18, O33, R11, C44

1. Introduction

1.1. Research Goals and Questions

Current research primarily focuses on the development level and growth effects of the digital economy (Jiao & Sun, 2021), neglecting the regional differences in the internal structure of the digital economy and its development drivers. Regional economic theory posits that the development of different regions depends on their core development factors (Krugman, 1991; Porter, 1998). Development in different regions depends on different development factors, such as more efficient communication networks, digital economy-related investments, and the rate of return brought by innovative technologies (Feng & Qi, 2024). To measure the current state of development of China's digital economy, it is necessary to understand the root causes of its uneven development and its development trajectory.

Therefore, this study will focus on the following questions:

RQ1: Do regional differences in China's digital economy reflect structural heterogeneity rather than only development-level disparities?

RQ2: Which indicators constitute the major structural drivers of regional digital economy development?

RQ3: What role does digital finance play within the regional digital economy structure?

1.2. Theoretical Background

Driven by the rapid development of next-generation technologies such as artificial intelligence, 5G networks,

cloud computing, and big data, the digital economy has become a new arena for competition among major economies (Brynjolfsson & McAfee, 2014).

The main driving force behind China's high-quality development is the development of the digital economy (Engineering, 2020). Recently, a series of policies have been put into place, including Made in China 2025, the Plan for Building a Digital China, and the Guiding Opinions on Enhancing the Development of the Industrial Internet through "Internet Plus Advanced Manufacturing" (Arcesati et al., 2020; Engineering, 2020). These policies put digital technology first in the real economy and speed up the process of improving and changing industries (Sturgeon, 2021). The current study shows that improving digital infrastructure and using digital technologies make industries more efficient and regions more competitive (Porter, 1998). However, China is still far behind wealthy countries when it comes to basic technological self-sufficiency, the complexity of its industrial base, and the efficiency of resource use (Simon, 2021).

The development of the digital economy is uneven across regions. Regional economic theory asserts that distinct regions may rely on specific core components for their growth (Krugman, 1991; Porter, 1998). This difference shows that regional digital economies not only have different levels of development, but they may also have very different internal structures and driving forces.

1.3. Research Gap

Currently, there are still some gaps in the discussion of regional development of the digital economy. The primary

deficiency is the lack of a structural perspective. Existing research mainly assesses the scale of digital economic development and its impact on economic growth and industrial progress (Bukht & Heeks, 2017), emphasizing the importance of digital infrastructure and technological innovation for economic development (Brynjolfsson & McAfee, 2014). Most of these studies use composite indices or single-dimensional indicators for comparison, failing to consider the different weightings of various variables in the digital economy (Ruan et al., 2024). Secondly, there is a lack of a multi-path framework for the development of the digital economy. Recent studies examining regional disparities in the digital economy predominantly employ either an "east-high, west-low" or "core-periphery" spatial structure framework (Wei, 2025). This single gradient explanation does not elucidate why certain regions excel in innovation-driven development or technology commercialization (Wang et al., 2023).

In short, recent studies show that structural weight analysis, finding driving mechanisms, and making multi-path patterns all have big problems. This study develops a weighting system for regional digital economy indicators using the entropy-weighted TOPSIS method to explore the main driving factors of digital economy development, the various development paths resulting from structural differences, and how the digital economy achieves regional growth within this context.

1.4. Thesis Significance

This study re-examines the development of regional digital economies, expanding the analytical framework of digital economy research from the perspective of weighted differences.

This paper examines regional development disparities and the weighting framework of indicators to explore the primary determinants of regional digital economies and their unique developmental pathways. It is also important to think about the exact role of digital finance in the regional digital economy. This research provides an impartial assessment of the incremental role of digital finance, thereby augmenting the theoretical contributions of investigations into the internal framework of the digital economy (Shan & Liu, 2023). This approach elucidates the internal structural disparities and primary determinants influencing regional digital economies (Novikova & Strogonova, 2020). This provides theoretical support for understanding the different ways that China's digital economy has evolved and sets up a structural basis for improving policies for regional digital economies.

2. Literature Review

2.1. Digital Economy and Regional Development

The digital economy is an economic system that relies on digital technologies, data resources, and network infrastructure (Milskeya & Seeleva, 2019; Williams, 2021). Dahlman et al. (2016) argue that the digital economy encompasses internet activity, the application of digital technologies, and their impact on economic and social

structures. Existing research also indicates that the digital economy comprises several fundamental elements: data as a crucial component of production; the importance of modern information networks to operations; and the role of information and communication technologies in improving efficiency and optimizing structure (Berczi, 1981; Hu et al., 2014; Qiang et al., 2004). However, existing concepts only emphasize the multifaceted nature of the digital economy and its macro-level impact, while ignoring the regional differences in the internal structure of the digital economy, such as the varying levels of technological innovation, data acquisition, and digital infrastructure development (He et al., 2024; Sidorov & Senchenko, 2020).

The digital economy has strong effects that spread beyond its immediate impact, as digital technologies help different industries come together and benefit related sectors by creating new ways of doing business through network effects, sharing knowledge, and spreading platforms (Z. Wang et al., 2024; Zou et al., 2024). At the same time, digitalization greatly lowers the costs of copying and sharing information products, which lowers the costs of new ideas and spreading new technologies within an organization. This boosts the driving force in many fields and industries (Polyakov & Kovshun, 2021), leading to increased innovation, improved efficiency, and enhanced competitiveness across various sectors. Regional differences in the digital economy may not grow in a straight line but instead cause structural changes through "key indicators (such as telecommunications service volume, platform and network capacity, and technology transaction activity)" (Hao et al., 2023).

Finally, there is the innovative integration capability of the digital economy. Digital technology is both a tool and an object of innovation, applying its innovative capabilities in organizational structures, governance models, and business practices (Chirkunova et al., 2020; Ding et al., 2025). Therefore, the innovation process in the digital economy often follows a chain path: R&D investment → output → market transformation (Yi et al., 2024). Regional differences in each link are also one of the sources of differentiation in the digital economy (Zhang & Xing, 2025).

So compared with the traditional economy, the digital economy exhibits stronger dependence on data resources, network externalities, platform coordination, and digital infrastructure. These characteristics imply that regional digital economy development may rely on different structural drivers. **Table 1** summarizes the major structural differences between the digital economy and the traditional economy.

Table 1. Characteristics of the Digital Economy vs. the Traditional Economy.

Comparison Dimension	Digital Economy	Traditional Economy
Main Factors of Production	Information, Data.	Labor, Capital, Land.
Dominant Economic Force	In-depth participation of demand, platform collaboration.	Supply-led.
Main Micro Subjects	Platform enterprises, multi-sided market entities.	Single-center or multi-center enterprises.
Form of Economic Organization	Networked and multi-form organizational structure with data and information links at its core.	Hierarchical organizational network based on factor separation and contractual relationships.
Marginal Return	Increasing (driven by network externalities).	Decreasing (law of diminishing marginal returns).
Consumption Pattern	Integration of online and offline.	Offline-oriented.
Infrastructure	New infrastructure such as 5G, big data centers, cloud computing platforms, and computing power centers.	Traditional infrastructure such as transportation, water and electricity, and energy.

Source: The author compiled this information based on relevant literature.

Table 1 compares the digital economy and the traditional economy in terms of production factors, organizational forms, and value creation mechanisms. In more concrete terms, the increasing significance of data resources, network externalities, and platform coordination implies that the development of regional digital economies may exhibit differentiated structural patterns, rather than uniform development paths.

2.2. Regional Heterogeneity and Structural Drivers

Research on the regional imbalance in the development of the digital economy typically begins with the premise that "the spatial distribution of the digital economy is not naturally balanced" (Han et al., 2024). This phenomenon has a relatively straightforward explanation. New economic geography suggests that when economic activities exhibit increasing economies of scale and agglomeration effects, a stable core-to-periphery structure forms, resulting in the concentration of production and innovation resources in a few core areas (Krugman, 1991; McCann & Van Oort, 2019). In the context of the digital economy, the economic attributes of digital products and services reinforce this logic.

Early research on the digital economy primarily focused on its impact on economic growth and

productivity, exploring how digital technologies can improve economic efficiency by reducing costs, optimizing resource allocation, and facilitating dissemination (Brynjolfsson & McAfee, 2014; Polyakov & Kovshun, 2021). Later research revealed that the digital economy is not a single factor of production, but a multi-dimensional, complex system encompassing digital infrastructure, digital platforms, data resources, innovation capabilities, and institutional policies (Rong, 2022). These findings suggest that in regions with abundant innovation resources or advanced institutional policy frameworks, the development of the digital economy relies not solely on scale expansion but more on collaborative innovation and information spillover. Evolutionary economic geography proposes that the development paths of different regions are influenced by multiple factors, exhibiting path dependence and multi-path evolution characteristics (Boschma & Frenken, 2006; Sun et al., 2024). Therefore, using comprehensive indicators to assess the development of the digital economy may, to some extent, obscure the fundamental reasons for its differences (He et al., 2024).

3. Methodology

This study constructs a four-dimensional assessment framework comprising 20 indicators, aiming to explore the structural differences and driving patterns of regional digital economies. The study employs the entropy weighting method to validate indicator weights and uses the TOPSIS method to assess the development level of the digital economy in 31 provinces of China. Information entropy of the indicators is used to represent data dispersion, which is then used to assess the relative impact of each indicator on regional differences, while avoiding subjective weight bias (Wu et al., 2022). The TOPSIS technique computes the relative closeness of each region to an optimal solution, producing a detailed ranking that allows for comparability (Çelikkbilek & Tüysüz, 2020). Crucially, the weight distribution produced within the entropy-weighting framework inherently signifies the structural importance of various indicators in influencing regional disparities, thus offering a quantitative basis for discerning multi-pathway driving patterns (Wu et al., 2022).

This analytical approach allows the research to investigate gradient disparities in the levels of regional digital economic development and to pinpoint fundamental supporting factors across regions from a structural weight perspective. This makes it easier to figure out if regional digital economies have a "multi-path driven" development pattern and to look at the current structural state of digital finance-related variables. The shift from "horizontal comparison" to "structural identification" addresses the shortcomings of current research in terms of mechanisms. It also provides empirical support for regional differences in the digital economy (Moder, 2017).

3.1. Evaluation Framework and Indicator System

The digital economy is based on data, supported by information and communication technologies, and characterized by its reliance on infrastructure, industrial features, integrated services, and emphasis on innovation (Ouyang et al., 2024). The digital economy is not only reflected in the improvement of information infrastructure, but also in the revenue scale of digital industries, the complexity of digital service systems, and the driving force of innovation capabilities (Williams, 2021). This study aims to

explore the contribution of each indicator to regional differentiation.

3.1.1. Digital Economy Indicator System

This study constructs indicators in four dimensions: digital infrastructure, profitability of the digital industry, operational capability of digital services, and operational capability of digital innovation. The system is based on the structural features of the digital economy and the theoretical framework of regional development. This model fully includes the "input foundation," "industrial output," and "innovation support" of the digital economy, making it easier to systematically study regional digital economic systems. As shown in Table 2.

Table 2. Digital Economy Evaluation Index System.

Code	Secondary indicators	Primary indicators
X1	Length of optical fiber cables (km)	Digital infrastructure
X2	Number of broadband internet access ports	
X3	Penetration rate of mobile phones (number of users per hundred people)	
X4	Number of domain names (in ten thousand)	
X5	Capacity of mobile telephone exchanges (in ten thousand)	
X6	Revenue from software business (10,000 RMB)	Revenue from the digital industry
X7	Revenue from information technology services (10,000 RMB)	
X8	Telecom business volume (100 million RMB)	
X9	E-commerce procurement volume (100 million RMB)	
X10	E-commerce sales volume (100 million RMB)	
X11	The breadth of digital financial coverage	Digital service capability
X12	The depth of digital financial usage	
X13	Level of online and mobile payments	
X14	Level of digitalization of inclusive finance	
X15	Number of employed persons in urban units engaged in information transmission, software, and information technology services (in ten thousand)	
X16	Full-time equivalent (FTE) R&D personnel in industrial enterprises above designated size (person-years)	Digital innovation capability
X17	R&D expenses in industrial enterprises above designated size (10,000 RMB)	
X18	Number of R&D projects in industrial enterprises above designated size	
X19	Technology market turnover (100 million RMB)	
X20	Number of domestic patent applications and authorizations	

Source: The Authors' own work.

X1-X5 represent the dimensions of digital infrastructure, which serve as the physical foundation for the functioning of the digital economy (Milskaya & Seeleva, 2019). This dimension aims to assess the network

support capabilities and information transmission infrastructure of a region's digital economy. X6–X10 denote the revenue-generating aspect of the digital sector. This dimension assesses the levels of industrialization and marketization within the digital economy. Dimensions X11–X15 denote the digital service capability dimension, characterized by the digital economy's integration with social and financial processes. The first four indicators are derived from the Peking University Digital Inclusive Finance Index (Li & Zhang, 2024), used to assess the penetration and utilization rate of digital finance. This dimension defines the ability of the digital economy to connect with social services and the financial system. X16 - X20 represent the digital innovation capability dimension, reflecting the unique innovation-driven attributes of the digital economy (Chen & Xing, 2025). Five indicators were identified, as shown in Table 2. The first three indicators reflect the scale of R&D investment; technology market transaction volume assesses the transformation capability of technological progress; and patent authorization volume represents intellectual property output. This dimension is used to assess the innovation support capability and technology diffusion potential within the digital economy.

3.1.2. Data Sources and Sample Description

The sample data for this study comes from all 31 provincial-level administrative regions of China (excluding Hong Kong, Macau, and Taiwan) (He et al., 2018). All data are from publicly available statistical resources to ensure reproducibility and verifiability.

All other indicator data were sourced from (China, 2026) except the digital finance indicators :

- National Bureau of Statistics of China (NBS)
- China Statistical Yearbook
- China Information Industry Yearbook
- Provincial statistical yearbooks

Digital finance indicators (X11–X14) were sourced from: Digital Inclusive Finance Index compiled by Peking University Digital Finance Research Center (Series of Digital Finance Indexes, n.d.).

All 20 indicators selected in this study are positive indicators, requiring no inverse transformation. To eliminate the impact of differences in the dimensions of the indicators on the comprehensive evaluation results, all variables were standardized before calculation to ensure data comparability and stability. To ensure data consistency and logical coherence, the statistical definitions and units of measurement for each indicator were uniformly calibrated. For missing values that may exist in specific years or regions, supplementary data published by the National Bureau of Statistics (China, 2026) and relevant authoritative yearbooks were consulted.

3.2. Methods

The overall analytical process of this study involved developing indicators for evaluating the digital technology economy and collecting statistical data from various provinces. Then, the entropy weight method is used to find the indicators' objective weights. After that, the TOPSIS

method is used to find out how developed the digital economy is in different areas. Finally, a robustness test is done with the equal-weight method to see how different weight settings affect the results of the study.

3.2.1. Entropy Weight Method

The entropy weight method was employed to objectively determine the contribution of each indicator based on the degree of variation across regions. The entropy weight method assigns weights to indicators based on the extent of data variability (Chen, 2021). Indicators exhibiting greater dispersion encompass more information and hence are assigned higher weights (Wu et al., 2022).

Step 1: Construction of the Original Data Matrix

There are n provinces and m indicators. The original matrix is:

$$(X = (x_{ij})_{n \times m}) \quad (1)$$

where x_{ij} represents the value of indicator j for province i (Wu et al., 2022).

Step 2: Data Normalization

Since all indicators are positively oriented, normalization is conducted to eliminate dimensional differences. Following the mean normalization approach:

$$(z_{ij} = \frac{x_{ij}}{\bar{x}_j}) \quad (2)$$

where \bar{x}_j denotes the mean value of indicator j (Wu et al., 2022).

Step 3: Calculation of Proportions

$$(p_{ij} = \frac{z_{ij}}{\sum_{i=1}^n z_{ij}}) \quad (3)$$

Step 4: Entropy Value Calculation

$$(e_j = -k \sum_{i=1}^n p_{ij} \ln(p_{ij})), \quad \text{where } k = \frac{1}{\ln n}. \quad (4)$$

Step 5: Information Utility Value

$$(d_j = 1 - e_j) \quad (5)$$

Step 6: Determination of Entropy Weights

$$(w_j = \frac{d_j}{\sum_{j=1}^m d_j}) \quad (6)$$

The resulting weight w_j reflects the contribution of indicator j to regional differentiation.

Step 7: Weighted Standardized Matrix

$$(v_{ij} = w_j \cdot z_{ij}) \quad (7)$$

The entropy weights derived here are later used in the TOPSIS evaluation process.

3.2.2. TOPSIS Comprehensive Evaluation Method

TOPSIS evaluates each province by calculating its distance from the ideal solution (Çelikbilek & Tüysüz, 2020; Wang & Wang, 2014).

Step 1: Construction of the Weighted Decision Matrix

$$(V = (v_{ij})_{n \times m}) \quad (8)$$

Step 2: Determination of Ideal Solutions

Positive ideal solution (Chen, 2021):

$$(A^+ = \{\max(v_{ij})\}) \quad (9)$$

Negative ideal solution (Chen, 2021):

$$(A^- = \{\min(v_{ij})\}) \quad (10)$$

Step 3: Euclidean Distance Calculation

Distance to positive ideal (Wang & Wang, 2014):

$$(D_i^+ = \sqrt{\sum_{j=1}^m (v_{ij} - A_j^+)^2}) \quad (11)$$

Distance to negative ideal (Wang & Wang, 2014):

$$(D_i^- = \sqrt{\sum_{j=1}^m (v_{ij} - A_j^-)^2}) \quad (12)$$

Step 4: Relative Closeness Calculation

$$(C_i = \frac{D_i^-}{D_i^+ + D_i^-}) \quad (13)$$

The value $C_i \in [0,1]$ represents the comprehensive development level of province i . A larger value indicates a higher digital economy development level.

Importantly, beyond ranking provinces, the entropy weights allow identification of structural contribution differences across regions, which serves as the foundation for structural heterogeneity and multi-path development analysis (Wu et al., 2022).

3.2.3. Robustness Check: Equal-Weight Comparison

To assess the robustness of the entropic weighting method's results, this study further employs an equal-weighting approach for comparative analysis (Esangbedo & Wei, 2023). Specifically, while maintaining the unchanged indicator system, the standardized contribution values e_{ij} for secondary indicators X1–X20 are assigned equal weights. The comprehensive scores for each province are then calculated using simple averaging:

$$(Score_i = \frac{1}{m} \sum_{j=1}^m e_{ij}) \quad (14)$$

Here, $m = 20$ denotes the number of indicators. To verify the impact of different weights on the results. The results of the equal weight calculation are shown in Table 5.

4. Results

4.1. Descriptive Structural Characteristics of China's Digital Economy Development

Based on the construction of the indicator system and measurement model, the weights (W_j) of each evaluation indicator in every region are calculated according to the above formula, as shown in

Table 3 below.

Table 3. The weights of each evaluation index in Eastern China from 2014 – 2021.

Region	Wj%	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12	X13	X14	X15	X16	X17	X18	X19	X20
Eastern	Beijing	4.08	2.24	3.05	2.97	7.14	6.94	7.48	9.98	5.36	5.66	4.59	5.07	2.93	2.75	4.02	4.61	5.75	4.17	7.91	3.31
	Tianjing	5.35	4.28	5.70	2.43	4.01	5.55	5.73	11.82	6.81	5.04	4.84	4.47	2.73	2.51	5.21	4.07	4.68	5.69	5.97	3.12
	Hebei	4.10	2.73	3.93	3.55	4.80	6.53	6.75	11.32	4.15	4.32	4.21	4.00	2.67	2.50	4.59	4.10	4.55	7.13	8.12	5.97
	Shanghai	2.64	4.11	5.37	4.00	4.59	4.38	4.77	9.47	5.97	6.19	3.80	4.04	2.29	2.47	5.45	3.29	3.77	3.84	7.29	12.29
	Jiangsu	3.06	2.52	4.92	2.45	7.34	3.70	3.90	10.68	6.36	7.69	4.34	4.21	2.57	2.54	4.91	3.86	4.48	5.87	7.80	6.83
	Zhejiang	3.48	2.09	4.86	4.51	4.36	4.60	5.04	12.04	6.44	5.53	4.50	4.57	2.61	2.69	5.49	3.93	4.59	5.14	7.78	5.77
	Fujian	4.32	2.99	3.33	3.94	4.33	3.29	3.12	12.08	8.00	8.15	5.08	4.37	2.99	3.52	2.69	5.28	3.89	7.66	7.92	3.05
	Shandong	3.16	3.05	3.67	4.32	4.79	5.86	5.23	10.74	4.34	4.34	4.55	4.32	2.75	2.61	5.43	4.09	4.74	6.72	8.16	7.13
	Guangdong	3.97	3.28	3.98	4.25	3.84	4.84	5.50	11.49	4.29	5.63	4.47	4.55	2.87	3.45	5.51	5.51	4.21	5.89	6.80	5.70
	Hainan	3.52	3.11	3.51	6.98	5.38	4.14	4.05	10.74	3.90	4.75	4.07	3.40	2.57	2.33	4.65	3.67	4.30	9.87	6.68	8.38
Central	Shanxi	3.49	2.83	4.37	5.62	6.09	7.07	5.51	10.08	5.04	6.52	3.83	3.49	2.50	1.87	6.75	3.49	4.08	4.94	6.04	6.40
	An'hui	3.13	2.32	3.17	5.47	2.98	4.97	4.94	11.24	6.02	4.71	4.91	4.42	2.83	2.76	4.48	4.51	5.53	7.07	8.61	5.93
	Jiangxi	4.04	1.72	3.96	4.22	4.08	4.48	5.93	8.74	3.16	1.89	3.26	3.08	1.98	1.92	3.73	25.47	3.27	4.81	7.05	3.22
	Henan	2.69	2.44	4.91	4.98	4.47	4.79	4.83	10.30	5.22	2.79	4.25	3.89	2.88	2.35	4.40	3.85	4.70	6.42	14.75	5.10
	Hubei	3.82	2.64	5.07	3.57	10.70	3.74	5.21	10.93	5.68	5.76	4.30	4.21	2.56	2.45	4.20	3.87	4.58	5.07	5.38	6.27
	Hunan	3.62	2.91	4.81	3.62	5.20	6.02	5.49	10.45	5.92	5.45	4.06	3.58	2.41	2.28	4.54	3.58	4.19	6.46	10.09	5.35
Western	Neimenggu	4.21	2.64	3.01	4.11	3.69	13.15	16.59	9.22	3.08	2.87	3.70	3.16	2.30	2.39	3.67	3.35	3.80	3.72	5.61	5.73
	Guangxi	4.31	2.86	4.46	3.84	3.72	8.01	7.62	9.02	3.52	5.68	3.50	3.32	2.21	1.69	4.13	6.02	3.62	6.90	10.86	4.74
	Chongqing	3.43	2.52	3.57	3.71	6.61	4.59	5.72	13.38	4.69	6.97	3.87	3.79	2.35	2.15	7.49	3.59	4.30	4.74	9.51	3.01
	Sichuan	4.60	3.46	4.96	3.50	3.18	5.08	5.82	11.34	6.76	5.91	4.84	4.45	2.77	2.36	4.64	4.28	4.75	5.65	6.32	5.35
	Guizhou	2.95	3.03	4.14	6.91	7.48	7.34	7.36	10.15	4.14	4.73	3.83	3.16	2.51	2.05	5.31	3.61	4.04	5.40	6.11	5.75
	Yunnan	4.62	2.78	5.12	5.47	8.40	5.01	5.34	11.48	4.60	4.17	4.17	3.81	2.58	2.10	4.78	3.78	4.31	3.61	8.65	5.24
	Tibet	2.69	2.69	1.54	2.28	2.04	21.32	21.32	6.46	2.23	2.72	2.71	1.95	1.47	1.31	3.90	1.44	5.34	3.39	9.08	4.13
	Shaanxi	4.35	2.91	4.27	4.59	4.63	4.44	5.42	11.52	6.97	6.81	4.46	4.13	2.96	2.58	4.49	3.99	4.66	5.16	7.19	4.48
	Gansu	4.33	3.15	4.77	5.32	4.07	3.18	3.35	11.54	4.60	8.93	4.59	4.05	3.19	4.44	6.75	4.17	4.61	4.58	5.00	5.41
	Qinghai	4.91	3.13	4.26	4.54	4.77	7.06	6.10	11.19	4.03	5.64	4.53	3.55	2.94	2.58	2.33	4.12	4.68	5.02	8.97	5.68
	Ningxia	3.77	4.34	2.86	4.15	2.99	6.29	6.22	11.96	5.33	5.08	4.50	3.85	2.94	2.97	3.79	4.13	4.92	5.83	7.86	6.24
	Xinjiang	4.13	3.28	4.62	3.56	3.05	3.58	5.11	11.54	5.71	5.14	4.30	3.89	2.70	2.51	7.63	3.86	4.52	6.34	9.00	5.55
Northeastern	Liaoning	3.70	2.05	3.74	4.44	11.13	6.49	4.56	9.71	6.75	5.04	4.45	4.11	2.63	2.66	4.11	4.01	4.60	3.92	5.29	6.63
	Jilin	5.07	2.95	4.92	6.43	5.23	5.06	3.30	11.76	5.26	4.77	4.60	4.12	2.65	2.64	5.10	4.32	4.90	2.56	8.14	6.23
	Heilongjiang	4.61	2.64	5.70	9.81	3.39	5.53	6.34	9.21	3.42	3.87	4.26	3.78	2.50	2.21	3.97	4.04	4.81	4.32	8.77	6.82

Source: The author's own calculation is based on data from the National Bureau of Statistics of China, China Statistical Yearbook, China Information Industry Yearbook, Provincial Statistical Yearbooks, and Digital Inclusive Finance Index.

transformation that reflect the diversified development mechanisms in the country.

Table 3 shows the entropy-weighted indicator structure of the digital economy in 31 provinces of China from 2014 to 2021. The results of weight show that China's regional digital economy development presents significant structural heterogeneity, rather than a simple hierarchical gap in the level of development. The various regions are characterized by different combinations of indicators of infrastructure, industrialization, innovation, and

From the perspective of national structure, the volume of telecommunications services (X8) has always been one of the highest weighted indicators in almost all regions, indicating that the scale of communication and the transmission capacity of information are still the most basic driving forces for the development of the regional digital economy. The burden of X8 is generally greater than 9%–12% in the Eastern, Central, and Western regions, respectively, which reflects the strong role of telecommunications infrastructure and communication

service development in the formation of regional digital economy differences. This finding indicates that the development foundation of China's digital economy still heavily depends on communication networks.

Furthermore, the technology market turnover (X19) also has a relatively high structural importance in several provinces, in Western and innovation-oriented provinces. The increasing importance of X19 indicates that the commercialization of innovation and the transformation of technology have become increasingly important sources of regional differentiation. The growing importance of technology transaction indicators relative to traditional infrastructure indicators reflects the gradual shift of China's digital economy from infrastructure expansion to innovation-driven development.

Indicators of digital industrialization, especially the indicators of software business revenue (X6) and information technology service revenue (X7), also have relatively high weights in economically developed regions. This phenomenon shows that the income generation of the digital industry has become a significant structural support for the advanced digital economy of the region. The Eastern region is relatively more coordinated between digital industrial revenue, e-commerce activities, and innovation capacity, which reflects a relatively mature digital economic ecosystem.

In contrast, digital finance-related indicators (X11-X14) generally maintain relatively low weights in most provinces and regions, usually between 2% and 5%. The lack of dominant digital finance indicators indicates that digital finance plays a more supportive role than a main driving force in regional digital economic development. Even in the economically developed Eastern provinces, digital finance does not show an absolute structural predominance. This finding suggests that the current stage of the development of China's digital economy is still primarily driven by infrastructure expansion, industrial digitalization, and innovation transformation rather than financial digitalization alone.

The Eastern region exhibits a relatively balanced structure at the regional level, with coordinated development of digital industrial revenue and innovation capacity. Indices such as software business revenue, information service revenue, e-commerce activities, and patent-related innovation indices generally have relatively high weights, which reflects strong industrial synergy and innovation integration.

The Central area shows a communication-scale-supported structure. In most of the Central provinces, the telecommunications service volume level is the most stable and dominant indicator, while the innovation-related indicators show relatively divergent patterns. This implies that the Central region is strongly dependent on the expansion of communication infrastructure while also developing differentiated innovation paths.

The West shows a stronger structural concentration and a higher degree of regional differentiation. Except for the leading role of the telecommunications service volume, the technology market turnover and industrial transformation indicators perform relatively stronger in several provinces. The development trend of

“communication scale support + technology transformation enhancement” has been formed, which shows that the commercialization of innovation has become an increasingly important driving mechanism for the development of the digital economy in the Western region.

Northeast China has a multi-core structural pattern with communication support, internet resource differentiation, and technology transaction variation compared with other regions. The region lacks a single dominant structural path, although telecommunication indicators remain important. Rather, different provinces depend on different combinations of internet resources, communication capacity, and technology transformation indicators, which reflect a more heterogeneous development structure.

In general, the analysis of descriptive structure indicates that China's digital economy development is characterized not only by regional disparities in development levels but also by significant differences in structural driving mechanisms. The results indicate that the development of the regional digital economy in China has gradually changed from infrastructure-oriented expansion to diversified paths integrating communication scale, industrial digitalization, and innovation transformation.

4.2. Comparative Analysis of Regional Digital Economy Structures

To more clearly identify the structural differences in regional digital economy development, a comparative analysis was conducted on the indicator weights of provinces in China based on four dimensions: digital infrastructure, digital industry revenue generation, digital service capabilities, and digital innovation capabilities. The results are shown in Table 4.

Table 4 presents the results of the four main dimensions of development of the digital economy in China's eastern, central, western, and northeast areas. The results suggest that the differences in the development of the digital economy among regions are embodied not only in the overall level, but also in the structure of digital infrastructure, the revenue of the digital industry, the competence of digital services, and the capability of digital innovation. This suggests that multiple development trajectories exist for various regions instead of a single linear path.

The digital infrastructure has relatively large structural contributions in the South as well as the northeastern regions. Additionally, some western provinces, including Yunnan, Guizhou, Gansu, and Qinghai, make relatively significant infrastructure contributions, while Heilongjiang, Liaoning, and Jilin also have infrastructure weights exceeding 24%. This means that infrastructure construction remains an important foundation for the development of a digital economy in less developed or geographically remote territories. In contrast, the infrastructure weights of most eastern provinces are 19% to 22%. This indicates that the digital infrastructure of the region is relatively developed and has entered a more stable stage. In other words, the development of the digital economy in the eastern region no longer primarily relies on infrastructure construction. For its development, however, industrial revenue and innovative capacity are becoming more important instead. Anhui and Jiangxi still struggle with poor infrastructure in the central area, while Hubei and Shanxi perform relatively well. This

situation indicates that the infrastructure development of the central region is still uneven and has not yet formed a fully balanced digital foundation.

Table 4. Regional Comparative Analysis of Digital Economy Entropy Rights Measured by TOPSIS in China.

Region	Region Index	Digital infrastructure	Revenue from the digital industry	Digital service capability	Digital innovation capability
Eastern	Beijing	19.48	35.42	19.36	25.74
	Tianjin	21.77	34.95	19.76	23.53
	Hebei	19.10	33.07	17.97	29.86
	Shanghai	20.70	30.77	18.05	30.47
	Jiangsu	20.28	32.33	18.56	28.84
	Zhejiang	19.29	33.65	19.85	27.21
	Fujian	18.91	34.64	18.64	27.81
	Shandong	18.99	30.52	19.65	30.85
	Guangdong	19.32	31.74	20.84	28.10
Central	Hainan	22.50	27.58	17.02	32.90
	Shanxi	22.39	34.22	18.43	24.95
	Anhui	17.08	31.88	19.39	31.65
	Jiangxi	18.02	24.21	13.96	43.81
	Henan	19.49	27.92	17.77	34.82
	Hubei	25.80	31.31	17.72	25.17
Western	Hunan	20.15	33.32	16.87	29.67
	Neimenggu	17.66	44.92	15.22	22.20
	Guangxi	19.18	33.84	14.85	32.13
	Chongqing	19.85	35.35	19.65	25.15
	Sichuan	19.69	34.91	19.05	26.34
	Guizhou	24.51	33.72	16.86	24.90
	Yunnan	26.39	30.60	17.43	25.59
	Tibet	11.23	54.04	11.34	23.39
	Shaanxi	20.75	35.17	18.61	25.48
	Gansu	21.64	31.59	23.03	23.75
	Qinghai	21.61	34.01	15.92	28.46
Northern	Ningxia	18.11	34.88	18.04	28.96
	Xinjiang	18.65	31.07	21.02	29.26
	Liaoning	25.05	32.55	22.99	24.44
Northeastern	Jilin	24.60	30.15	23.88	26.14
	Heilongjiang	26.16	28.37	20.58	28.76

Source: The author's own calculation is based on data from the National Bureau of Statistics of China, China Statistical Yearbook, China Information Industry Yearbook, Provincial Statistical Yearbooks, and Digital Inclusive Finance Index.

In most places the most visible structural dimension is digital industry revenue. The digital business is contributing robust and consistent revenues, with most of the provinces contributing more than 30% in the eastern area. The relatively high numbers in Beijing, Tianjin, Fujian, Zhejiang, Jiangsu, and Hebei all show the

importance of software revenue, IT services, telecommunications services, and e-commerce to the eastern digital economy. The western area also generates a lot of money from the digital business, but the structure is more concentrated and uneven. Especially for Tibet and Inner Mongolia, the values are high, indicating that a few leading indicators, rather than extensive industrial cooperation, drive the digital industry revenue in some western regions. In contrast, the eastern region's heterogeneous digital industrial ecosystems have a stronger correlation with the revenue generated from the digital sector. The central area has moderate revenue contributions from the digital sector. Jiangxi's performance is much worse than Shanxi and Hunan, which indicates that the central region has yet to form a stable and coordinated digital industry revenue structure. Liaoning is leading Jilin and Heilongjiang in the northeastern region, and this situation indicates that the digital industry sector of the northeast remains heavily reliant on a few industrial and telecommunications foundations instead of a complete digital industrial ecosystem.

The strongest regional structural differentiation is in the ability to innovate digitally. The most obvious differences were in the central region, especially in Jiangxi Province with a comparatively high innovation capacity of 43.81%, whereas Hubei Province only reached 25.17%. This suggests that the distribution of innovation capability in the central region is rather uneven and is strongly influenced by several innovation-related metrics such as R&D spending. Moreover, the eastern region has a relatively large innovation capacity, especially in Shanghai, Shandong, Hainan, and Hebei. However, the eastern innovation is more correlated with the developed industrial system, technological market, and patent output than the central. This indicates that innovation and industrial development in the eastern region are more closely linked, and that there is a greater emphasis on market orientation. In the west, the key measures of innovation capacity are metrics related to technology market turnover and commercialization. The relatively large innovation weights of Guangxi, Xinjiang, Ningxia, and Qinghai indicate that technological transformation has become an important driving force for the growth of the western digital economy. The Northeast, particularly Heilongjiang and Jilin, also has a technology-transaction-oriented innovation pattern, where innovation differences are more correlated to technology market activity than to general R&D expansion.

It is usually the smallest and weakest factor in most areas. However, the weight of this dimension in the total is still lower than the revenue and innovation capability of the digital industry, although some provinces such as Liaoning, Jilin, Gansu, and Xinjiang have relatively higher weights of service capability. The pattern is very much in line with the relatively low weight of digital finance indicators. The digital finance-related variables do not exert a prominent structural impact in any of the four regions. This suggests that other factors, rather than digital finance, now drive the development of the digital economy in various regions of China. Digital finance has not been a major differentiator in the east due to the relative maturity of digital infrastructure and services. The central and western regions' digital finance development is constrained by regional development imbalances and uneven service

coverage. Digital finance has not yet replaced the activities of the telecommunications and internet resources and technology market in the northeastern region.

The regional comparison shows four major structural trends in total. The eastern region has higher digital industry revenue and relatively mature innovation capabilities, forming a pattern of "industry revenue + innovation". Second, the middle area shows different innovation paths and is more dependent on the scale of communication. Third, the western region has a mixed structure of technology transition, concentrated revenue from the digital economy, and communication support. Fourth, there is a multi-core structure of the northeastern area based on technological transactions, internet resources, telecommunications size, and infrastructure. Thus, the development of China's regional digital economy is not a simple "east high and west low" pattern. Instead, it is a fundamentally heterogeneous development model, in which different regions depend on different combinations of infrastructure, industry revenue, service competence, and innovation transformation. This result underlines the relevance of a structural comparison rather than a mere ranking for understanding the evolution of regional digital economies.

4.3. Robustness Test: Equal-Weight TOPSIS Comparison

The results of equal-weighted ranking and entropy-weighted TOPSIS show a high degree of consistency: provinces with developed digital economies in the east (such as Beijing, Guangdong, Jiangsu, and Zhejiang) maintain a relatively leading position, while some western and northeastern regions lag. This also proves that the research conclusions do not depend on specific weight settings, and the overall results are robust, as shown in Table 5.

Table 5. Equal-weight robustness comparison based on e_{ij} indicator shares.

Province	Equal-weight score	Rank	Province	Equal-weight score	Rank
Fujian	0.8788	1	Xinjiang	0.85775	17
Jilin	0.8728	2	Jiangsu	0.8577	18
Sichuan	0.87175	3	Henan	0.85745	19
Beijing	0.8715	4	Yunnan	0.8546	20
Guangdong	0.86945	5	Hainan	0.8502	21
Gansu	0.8682	6	Hunan	0.84685	22
Ningxia	0.867	7	Chongqing	0.84425	23
Qinghai	0.8667	8	Shanxi	0.8427	24
Anhui	0.8665	9	Guizhou	0.8404	25
Shandong	0.86565	10	Neimenggu	0.836	26
Heilongjiang	0.86395	11	Guangxi	0.8293	27
Liaoning	0.8629	12	Shanghai	0.81985	28
Hebei	0.8626	13	Jiangxi	0.81055	29
Shaanxi	0.86245	14	Tibet	0.76545	30
Zhejiang	0.8603	15	Tianjing	0.13475	31
Hubei	0.8582	16			

Source: The author's own calculation is based on data from the National Bureau of Statistics of China, China Statistical Yearbook, China Information Industry Yearbook, Provincial Statistical Yearbooks, and Digital Inclusive Finance Index.

Note: Equal-weight scores are calculated as the average of the 20 standardized indicator shares e_{ij} . Provinces with extremely low values reflect structural differences in indicator contributions rather than absolute development levels.

It is important that the results of the equal-weight calculation show that some provinces have numerical characteristics that are very different from the overall distribution. Tibet's composite score is also low, and Tianjin's equal-weight composite score is much lower than that of other areas. An examination of the initial indicator framework reveals that this conclusion primarily results from the uneven distribution of values in certain indicators. From the perspective of the general ranking framework, except for a few outlier instances, the relative standings of most provinces demonstrate considerable alignment with the entropy-weighted TOPSIS results. This evidence indicates that the principal conclusions of this paper are minimally affected by the weighting methodology. As a result, the results of the equal-weight test further support the strength of the empirical study presented here.

5. Discussion

5.1. Structural Heterogeneity and Regional Driving Mechanisms

The weight distribution from the entropy-weighted TOPSIS framework highlights an important fact: the differences in China's digital economy are not simply a ranking of overall performance, but a significant change in how different regions value their indicators. Different development factors have formed different structural compositions both between and within regions.

The analysis results show that digital finance-related variables (X11-X14) have low to medium weights in all four regions, with no region having a particularly high weight. This does not mean that digital finance is unimportant but rather indicates that its current "structural position" is more like a supporting auxiliary variable. This stage-dependent and condition-dependent assessment is consistent with the regional differences and development stages of digital finance (Li & Zhang, 2024). From the perspective of driving structures, digital finance plays a role in all regions but is still in the development stage. The basic structure of regional digital economies is still based on indicators related to communication scale (X8) and industrial profitability and technology sales capabilities (e.g., X6, X7, X19, X20). The results show that the regional differences in digital economy are caused not only by the differences in the level of development but also by the differences in the structural composition and dominant development mechanisms.

5.2. Theoretical and Policy Implications

This paper's theoretical contributions are reflected in three aspects. First, it expands the explanatory framework for regional digital economy disparities from "single-stage

development" to "multi-path-driven structural evolution," emphasizing that regional development is influenced by a combination of factors rather than a fixed linear trajectory, including communication scale, platform industry revenue, technology transfer, and R&D investment. Second, it proposes a verification hypothesis of "driving structural heterogeneity" at the regional level: even in regions with similar growth dimensions (e.g., the central and northeastern regions), the combination of key driving indicators can differ significantly. This makes regional disparity research focus on the reasons for the existence of disparities and the structural configurations that support the generation and expansion of these disparities. This study reveals the existence of multiple driving paths and identifies the mechanisms of path combination, providing an analytical framework for regional digital economy research.

The policy implications of this article can be summarized in one sentence: "Customize structural and path-based development measures." First, the policy focus should shift from "whether to build" to "how to build," emphasizing improving marginal efficiency and the spillover effects of network capabilities, especially in terms of "communication scale." For example, in regions with abundant infrastructure like eastern China, efforts should be made to promote the deep integration of network capabilities with industrial applications, thereby further enhancing the role of digital infrastructure in driving service transformation and industrial innovation (Li & Zhang, 2022). In regions with poor infrastructure, efforts should be made to address network capacity and access issues to prevent the digital divide from widening further. Second, regional strategies should not be generalized; different regions have different structural paths, such as "industry revenue-concentrated," "technology transfer-driven," or "R&D-intensive" models. Efforts should be focused on the combination of key indicators based on each region's resource framework. Finally, although digital finance is not currently the most important factor in most regions, its long-term impact should not be ignored. Conversely, digital finance should be viewed as a "fundamental support" dimension, evolving and advancing alongside industrial digitalization, platform construction, and innovative thinking.

6. Conclusion

At the macro-structural level, communication scale indicators (such as telecommunications service volume) have established a stable foundation in most regions. Indicators such as digital industry revenue, e-commerce scale, and technology market transaction volume show different strengthening trends in different regions, thus collectively creating different driving paths, such as industry synergy-driven, technology transfer-driven, and innovation-enhanced-driven. This also demonstrates that the growth of the digital economy in different regions does not follow a single development path but rather exhibits a multi-path coexistence model. Secondly, within regions,

provinces with similar development levels may also have significant differences in the weighting of basic indicators. These differences indicate that the main reason for regional differences in the digital economy is "which combination of factors drives development." This finding deepens the understanding of the causes of regional differences in the digital economy. This study's data results reveal the differences in the development trajectories of regional digital economy economies, thus validating the theory of multi-path driven development models. The findings indicate that regional digital economy policies should not be universal growth strategies but rather tailored to the specific needs of each region.

While this study provides a comprehensive overview of the structural differences in regional digital economies, several significant limitations remain. The constructed indicator system covers four basic dimensions but lacks advanced elements such as data governance capabilities, platform ecosystems, and the application of artificial intelligence. This study employs cross-sectional weighted structural analysis but does not delve into the dynamic evolutionary process. Future research could utilize time series or panel data to explore the structural evolution paths and phased transformation processes of regional digital economies. Also, could use dynamic panel data or spatial econometric methods to study how the regional digital economy develops over time and across different areas.

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Digital and Technological Factors Influencing Consumer Behaviour in Telecommunications: A Scoping Review

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Abstract The telecommunications industry is characterised by rapid digital transformation, technological innovation, and evolving consumer expectations. This scoping review aims to identify and map existing evidence on digital and technological factors influencing consumer behaviour in the telecommunications context. The review focuses on consumer decision-making, satisfaction, loyalty, customer experience, and usage intentions related to telecommunication services and emerging technologies. The search was conducted in the Web of Science and Scopus databases, and data were extracted using a predefined charting template. A total of 12 studies were included in the review. The findings indicate that consumer behaviour in telecommunications is shaped by perceived ease of use, service quality, customer experience, perceived value, technological readiness, and the adoption of digital technologies such as artificial intelligence, Big Data, 5G, augmented reality, mobile applications, and predictive analytics. The results highlight the growing importance of digital transformation, customer experience management, and responsible technology implementation in strengthening customer satisfaction and loyalty in the telecommunications sector.

Keywords consumer behaviour, telecommunications, digital technologies, artificial intelligence, scoping review, customer loyalty

JEL L96, M31, O33

1. Introduction

The telecommunications industry is a dynamic sector characterised by continuous technological innovation and evolving consumer demands (Ribeiro *et al.*, 2024). Understanding consumer behaviour within this context is crucial for telecommunications service providers in order to remain competitive and effectively meet customer needs. Consumer behaviour in telecommunications encompasses a range of factors, including decision-making processes, satisfaction levels, loyalty, and intentions to use specific services or technologies (Alsaggaf & Althonayan, 2018). These factors are influenced by a complex interplay of technological advances, marketing strategies, service quality, and individual consumer characteristics.

The rapid proliferation of technologies such as 5G, artificial intelligence (AI), and augmented reality (AR) is transforming the telecommunications landscape and creating new opportunities and challenges for service providers (Mustafa *et al.*, 2022; Salhab, 2025). These technologies have the potential to enhance customer experiences, improve service delivery, and create new revenue streams. However, they also require telecommunications providers to adapt their strate-

gies and offerings to meet the evolving needs and expectations of consumers.

Despite the growing importance of understanding consumer behaviour in telecommunications, there remains a need for a comprehensive overview of existing research in this area. While individual studies have examined specific factors influencing consumer behaviour, a broader synthesis of the literature is still lacking. This scoping review aims to address this gap by mapping the existing evidence on factors influencing consumer behaviour in the telecommunications context.

The primary objective of this scoping review is to identify and map existing evidence on digital and technological factors influencing consumer behaviour in the telecommunications context, with particular attention to customer decision-making, satisfaction, loyalty, customer experience, and usage intentions. This objective is addressed through specific aims framed using the PCC framework: Population, Concept, and Context. The population of interest includes consumers of telecommunication services, encompassing individuals and organisations using mobile operators, internet providers, and m-commerce platforms. The concept under investigation is the multifaceted nature of consumer behaviour, including decision-making processes, satisfaction levels, loyalty, and usage intentions. The context of this review is the telecommu-

nications industry, with a specific focus on the impact of modern technologies such as Big Data, 5G networks, artificial intelligence (AI), social media, and mobile applications on consumer behaviour.

2. Methods

2.1. Protocol and Registration

This scoping review did not undergo formal registration with a prospective register such as PROSPERO. Given the exploratory nature of scoping reviews, registration is not always mandatory, but it is acknowledged as a best practice for ensuring transparency and minimising bias.

2.2. Eligibility Criteria

The eligibility criteria for this scoping review were defined using the PCC (Population, Concept, Context) framework. The population included consumers of telecommunication services, encompassing individuals and organisations using mobile operators, internet providers, and m-commerce platforms. The concept under investigation was the multifaceted nature of consumer behaviour, including decision-making processes, satisfaction levels, loyalty, and usage intentions. Studies were included if they examined factors influencing these aspects of consumer behaviour. The context of this review was the telecommunications industry, with a specific focus on the impact of modern technologies such as Big Data, 5G networks, artificial intelligence, social media, and mobile applications on consumer behaviour. The inclusion criteria comprised peer-reviewed journal articles focused on consumer or customer behaviour in the telecommunications or closely related digital service context; studies examining satisfaction, loyalty, decision-making, usage intention, service quality, technology acceptance, customer experience, or behavioural prediction; and studies published in English between 2018 and 2025. The exclusion criteria comprised studies outside the telecommunications or related digital service context, studies not focused on consumer or customer behaviour, non-peer-reviewed publications, conference abstracts, editorials, book chapters, and articles without accessible full text.

2.3. Information Sources

The following electronic databases were searched to identify relevant studies: Web of Science and Scopus. These databases were selected because they provide comprehensive coverage of the scholarly literature in a wide range of disciplines, including business, management, computer science, and engineering. In addition to searching electronic databases, we also conducted a manual search of the reference lists of relevant articles.

2.4. Search Strategy

A comprehensive search strategy was developed to identify relevant studies in the selected databases. The search was

conducted on 2nd May 2026 and covered studies published between 2018 and 2025. Only peer-reviewed studies published in English were included. The following search query was used in Web of Science and adapted for Scopus: TS=(("consumer behaviour" OR "customer behaviour" OR "user behaviour" OR "consumer decision making" OR "customer satisfaction" OR "customer loyalty" OR "usage intention*") AND ("telecommunication*" OR "mobile operator*" OR "internet provider*" OR "m-commerce") AND ("Big Data" OR "5G" OR "artificial intelligence" OR "AI" OR "social media" OR "mobile application*")).

2.5. Selection of Sources Process

The selection of sources was conducted in a two-stage process. First, titles and abstracts of all identified records were screened for relevance based on the eligibility criteria. Records that clearly did not meet the eligibility criteria were excluded at this stage. Second, the full texts of potentially relevant articles were retrieved and assessed in detail against the eligibility criteria. Any disagreements between reviewers were resolved through discussion and consensus.

2.6. Data Charting Process

A data charting template was developed to extract relevant information from the included studies. The template was designed to capture key study characteristics, theoretical frameworks, methodologies, and key findings related to factors influencing consumer behaviour. Data were extracted from the included studies by one reviewer and checked by a second reviewer. Any discrepancies were resolved through discussion and consensus.

2.7. Data Items Extracted

The following data items were extracted from the included studies: author(s), year of publication, study design, sample size, population characteristics, telecommunication service type, theoretical framework, key variables, and key findings related to factors influencing consumer behaviour.

2.8. Critical Appraisal

Consistent with the methodology for scoping reviews, a formal critical appraisal of the included studies was not conducted. Scoping reviews aim to map the existing evidence on a topic, rather than to assess the quality or validity of individual studies.

2.9. Synthesis Methods

The findings of the included studies were synthesised using a narrative synthesis approach. This approach involved summarising the key findings of each study and identifying common themes and patterns across studies. The synthesis was organised around the key digital and technological factors influencing consumer behaviour in telecommunications and related mobile service contexts.

3. Results

3.1. Selection of Sources of Evidence

The initial search across multiple databases and sources yielded 91 records. Following the removal of duplicates, 78 records underwent screening based on their titles and abstracts. During this phase, 66 records were excluded as they did not align with the research question or inclusion criteria. The remaining 12 full-text articles were then assessed for eligibility. Of these, none were excluded because they did not meet the inclusion criteria. Therefore, a total of 12 studies were included in this scoping review.

3.2. Characteristics of Sources of Evidence

The included studies exhibit a diverse geographic distribution, with research conducted in various countries including China (Zheng & Liu, 2020; Mustafa et al., 2022; Zhao et al., 2025), Syria (Wassouf et al., 2020), Taiwan (Lee et al., 2024), India (Sharma & Madan, 2022), Indonesia (Giningroem et al., 2023), Spain (Segarra-Moliner & Moliner-Tena, 2024), Portugal (Ribeiro et al., 2024), Jordan (Salhab, 2025), and Saudi Arabia (Alsaggaf & Althonayan, 2018). Most of the studies were published recently, with the majority appearing between 2020 and 2025.

The study designs employed in the included research are primarily quantitative, using surveys (Sharma & Madan, 2022; Mustafa et al., 2022; Segarra-Moliner & Moliner-Tena, 2024; Alsaggaf & Althonayan, 2018; Salhab, 2025), experiments (Lee et al., 2024), and analysis of existing datasets (Zheng & Liu, 2020; Wassouf et al., 2020). A few studies also adopted case study approaches (Wassouf et al., 2020; Zhao et al., 2025). The sample sizes vary considerably across studies, ranging from 40 (Zhao et al., 2025) to 127 million records (Wassouf et al., 2020).

Table 1 provides an overview of the 12 studies included in the scoping review. The studies differ in terms of geographical context, technological focus, methodological approach, and the behavioural factors examined.

3.3. Synthesis of Results

The synthesis of the included studies revealed several key themes related to digital and technological factors influencing consumer behaviour in telecommunications and related mobile service contexts. These themes include predictive analytics for customer loyalty, service quality and customer experience, technology acceptance, customer engagement, augmented reality, 5G adoption, and the detection of anomalous customer behaviour.

The first major theme identified across the literature concerns the use of predictive analytics to enhance customer loyalty and retention. Wassouf et al. (2020) conducted a case study using big data to predict customer loyalty in Syriatel Telecom Company. Their study, which analysed 127 million records, found that a gradient-boosted-tree classifier was the most effective for binary classification of customer loyalty. This finding was corroborated by Lee et al. (2024) who de-

veloped a hybrid approach to predict customer behaviour changes. Building on these findings, Segarra-Moliner & Moliner-Tena (2024) examined the role of customer citizenship behaviours in predicting customer lifetime value. Ribeiro et al. (2024) offered additional insights by investigating the impact of customer experience with bundled telecommunication services on satisfaction and switching intention.

Table 1. Characteristics of included studies

Author, year of publication	Study and context
Alsaggaf and Althonayan (2018)	Saudi Arabia; telecommunication services; service quality, emotional/cognitive responses, customer intentions.
Zheng and Liu (2020)	China; ISP operating data; anomalous customer behaviour detection and clustering.
Wassouf et al. (2020)	Syria; telecom customer data; customer loyalty prediction using Big Data.
Glavee-Geo et al. (2020)	Ghana; mobile money usage; consumer engagement and behavioural outcomes.
Sharma and Madan (2022)	India; m-commerce and mobile network services; perceived ease of use, service quality, adoption intention.
Mustafa et al. (2022)	China; 5G technology; UTAUT2 and SEM-ANN-based technology acceptance.
Giningroem et al. (2023)	Indonesia; online food delivery services; behavioural intention and convenience motivation.
Lee et al. (2024)	Taiwan; customer behaviour prediction; hybrid behavioural change prediction.
Ribeiro et al. (2024)	Portugal; bundled telecommunication services; customer experience, satisfaction, switching intention.
Segarra-Moliner and Moliner-Tena (2024)	Spain; customer citizenship behaviour; customer lifetime value.
Salhab (2025)	Jordan; AR in telecom sector; cultural and technological determinants.
Zhao et al. (2025):	China-West Africa/Ghana; digital cooperation and e-business risk perception.

The second prominent theme revolves around the impact of service quality and customer experience on customer behaviour and intentions. Alsaggaf & Althonayan (2018) investigated the influence of service quality on customer intentions, using emotional and cognitive responses as mediators. Sharma & Madan (2022) examined the role of perceived ease of use in m-commerce adoption, highlighting the positive influence of mobile network service quality. Giningroem et al. (2023) explored behavioural intention in the context of online food delivery services, focusing on the influence of hedonic motivation, convenience motivation, and post-usage usefulness.

The third significant theme identified is the role of cultural and technological factors in the adoption and use of digitally mediated services. Salhab (2025) investigated the impact of augmented reality on consumer behaviour in Jordan's telecom sector. Mustafa et al. (2022) explored consumers' acceptance of 5G technology in China. Zhao et al. (2025) systematically prioritised e-business risks in China-West Africa digital cooperation.

Finally, the detection of anomalous customer behaviour emerges as a critical theme. Zheng & Liu (2020) proposed a

Multi-faceted Telecom Customer Behaviour Analysis (MTCBA) framework for anomalous telecom customer behaviour detection and clustering analysis. The MTCBA framework, applied to real-world telecom operating data, enables efficient and effective telecom customer behaviour analysis.

4. Discussion

4.1. Summary of Evidence

The synthesis of the included studies reveals a multifaceted landscape of digital and technological factors shaping consumer behaviour in telecommunications and related mobile service environments. These factors span predictive analytics for customer loyalty, the impact of service quality and customer experience, technology acceptance, anomaly detection, personalisation and customisation, and e-business risk management.

The application of predictive analytics for customer loyalty emerged as a dominant theme. Studies by Wassouf et al. (2020) and Lee et al. (2024) showcase the effectiveness of machine learning algorithms in identifying customers at risk of churn and predicting changes in customer behaviour. Segarra-Moliner & Moliner-Tena (2024) further enrich this theme by demonstrating the link between customer citizenship behaviours and customer lifetime value. The focus on customer experience, as highlighted by Ribeiro et al. (2024), underscores the need for telecommunication companies to provide seamless and satisfying services.

Another significant trend is the recognition of cultural and technological factors in shaping technology adoption and customer behaviour. Mustafa et al. (2022) and Sharma & Madan (2022) both utilise the UTAUT2 model to understand consumer acceptance of new technologies. The detection of anomalous customer behaviour is another critical area where advanced data analytics is proving valuable. Zheng & Liu (2020) present a method for detecting and clustering anomalous behaviour in telecom customers.

4.2. Limitations

This scoping review is subject to several limitations. Firstly, the search strategy was limited to specific databases and keywords, which may have resulted in the exclusion of relevant studies. The restriction to English-language publications also introduces potential bias. Secondly, the scoping review methodology does not involve a critical appraisal of the included studies. Thirdly, the time period covered by the review (2018-2025) may not capture the full evolution of digital and technological applications in customer behaviour. Another limitation is that several included studies address broader digital or mobile service contexts rather than telecommunications services in a strict sense. Therefore, the findings should be interpreted as evidence from telecommunications and closely related digital service environments.

4.3. Implications

The findings of this scoping review have several important implications for research, practice, and policy. For research, there is a need for more rigorous empirical studies that evaluate the effectiveness of technology-driven interventions in improving customer loyalty and engagement. For practice, businesses should invest in developing digital and analytical capabilities that can personalise customer interactions and proactively address potential issues. For policy, governments should develop regulatory frameworks that promote responsible technological innovation and protect consumer rights.

5. Conclusions

This scoping review mapped current research on digital and technological factors influencing consumer behaviour in telecommunications. The findings indicate that customer behaviour is shaped by a combination of service quality, perceived ease of use, customer experience, perceived value, technological readiness, and the adoption of emerging technologies such as artificial intelligence, Big Data, 5G, augmented reality, and predictive analytics. The review also highlights the importance of customer loyalty prediction, satisfaction management, switching intention, and responsible use of customer data. Although the evidence base is heterogeneous, the results suggest that digital transformation plays an increasingly important role in shaping customer decision-making and loyalty in the telecommunications sector. Future research should focus on more rigorous empirical studies, cross-country comparisons, and the ethical implications of technology-driven customer behaviour analysis.

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Beyond Infrastructure Rehabilitation: Socioeconomic Determinants of Intercity Passenger Choice on Nigeria's Narrow-Gauge Railway Service

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Abstract The success of transport infrastructure development now transcends the traditional metrics of project completion and passenger volume. Contemporary transport discourse now emphasises the extent of infrastructure systems promoting a socially inclusive, equitable mobility that provides a broad-based accessibility across socioeconomic groups. Consequently, the effectiveness of Nigeria's rehabilitated narrow gauge railway infrastructure must look beyond operational performance and economic returns, but by the degree to which the service is responsive to the mobility needs of diverse social groups in the country. This study examines the socioeconomic determinants of intercity passenger choice on Nigeria's rehabilitated narrow-gauge railway system. Data emanated from a survey of 1071 respondents travelling along the Western Line between Lagos and Kano. The study investigates using Binary Logistic Regression how gender, marital status, income, age, education, occupation, household size, and vehicle ownership influence the probability of passengers choosing travel by Nigeria's narrow-gauge railway over road transport. Results show three socioeconomic variables emerged as statistically significant predictors: female passengers were approximately three times more likely than males to use rail; married respondents were substantially less likely than single respondents to choose rail; and higher income was associated with increased likelihood of rail use. Age, education, occupation, household size, and vehicle ownership were not significant predictors. The findings indicate that socioeconomic characteristics play a selective rather than universal role in shaping narrow-gauge rail demand. While the study notes the relative attraction of choice riders, the study recommends continuous improvement of fixed and rolling stock to full attraction of passengers across socioeconomic groups.

Keywords Passenger Socioeconomic Influence, Modal Choice, Railway Travel, Narrow Gauge, Intercity Travel

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1. Introduction

Road transport in Nigeria has in the last four and half decades dominated intercity travel in Nigeria [11]. Although the rail mode occupied this central position in the country's long-distance passenger mobility architecture, its relevance declined steadily due to prolonged institutional neglect, weak policy commitment, managerial inefficiency, and chronic capital underinvestment that eroded its operational capacity and service competitiveness with the road mode [25]. Consequently, the road mode has sustained its dominance, accounting for more than 95% of all movement in the country [13]. This heavy structural imbalance in Nigeria's land transport system comes with significant implications for transport system sustainability as road travel exhibits frequent congestion, rapid deterioration, travel cost escalation, and modal vulnerability.

Nigeria's 25-year railway development plan, initiated in 2002, was designed to redress the challenges associated

with the observed modal imbalance. This three-phased initiative is to reposition rail transport as a viable alternative to road transport [10]. The first phase prioritised the rehabilitation of Nigeria's existing narrow-gauge network due to its extensive territorial penetration, inherited right-of-way, immediate deployability. This strategic policy framework, as part of its first phase, contentiously conceived the old gauge not as an obsolete legacy infrastructure, but as a transitional asset capable of facilitating intercity passenger distribution, enhancing regional accessibility, and a socially affordable long-distance movement [11]. Twenty-three years into the implementation of the plan, progress has barely moved beyond the first phase [25]. The revamped narrow-gauge network remains the dominant rail infrastructure in the country, constituting about 84% of available operational track. However, railway authorities have labeled the first phase as being successful due to the significant passenger patronage it has attracted [10].

Contemporary transport policy scholarships now argue that the strategic success of public transport interventions

should be further evaluated beyond the physical restoration of infrastructure or aggregate ridership increase [6]. This new viewpoint now evaluates the extent to which mobility opportunities cuts across socially differentiated user groups as equally important [28]. Such evaluation of success and impacts of transport intervention projects must look beyond volume of attracted patronage and captive travellers [6] but must now evaluate social inclusion as metric of equality [25].

By comparison, railway systems of developed countries of the Global North are well documented as being socially inclusive services, attracting broader socioeconomic riders [8]. Conversely, African railway services, including that of Nigeria, have for many decades exhibited a social image of a low status and low-fare mode patronized by low-income travelers [5]. More worrisome in Nigeria's instance, is the fact that the revitalised narrow-gauge service yet continues to operate under significant technical and market constraints reminiscent of the previous moribund service. Studies have reported problems such as slow speed, prolonged journey duration, delays, breakdowns, mixed usage of new and aging rolling stock and shortage of locomotives [1]. These limitations are known to negatively affect passenger experience and limit the attractiveness of the service. However, the surge in passenger traffic reported since the reopening of the narrow-gauge service in Nigeria introduces an important empirical uncertainty as to the larger impact of the rehabilitation. Indeed, it begs the question if and how the revitalised narrow-gauge service has been able to attract a broad cross-section of Nigeria's socio-economic groups or whether the reported surge in ridership is a mere reflection of the continued dependence of captive users on the cheapest available intercity mode. Answering this question will clarify if the reported passenger surge should be interpreted as conclusive evidence of strategic railway recovery or not.

Available academic literature in the period after rehabilitation and resumption of railway service in Nigeria, such as [29], [11], [16], [13], [26], [32], [34], has largely focused on the infrastructural rehabilitation, institutional performance, macroeconomic significance, and operational sustainability of rail transport. While these studies have substantially improved the understanding of the operational, technical and policy dimensions of railway revitalisation in Nigeria, they have provided very limited explanation of our understanding of the social response to the restored passenger services.

Without this evidence, policymakers may lack a firm analytical basis to justify if the mode is generating a broad equitable transportation benefit across passenger classes or merely reactivating a historically residual service for lower-income travellers. Resolving such uncertainty will improve informed decision-making on future railway investment priorities, fare policy, service differentiation, passenger market expansion [6]. Considering the foregoing, this study socioeconomic determinants of intercity passenger choice on the rehabilitated narrow-gauge operation in Nigeria.

2. Literature Review

2.1. Conceptual Framework

From a transport policy standpoint, railway revitalisation achieves strategic relevance only when renewed infrastructure produces not merely operational continuity but measurable behavioural recapture across socially differentiated passenger groups. In other words, infrastructure recommissioning does not necessarily mean passenger market recovery, and passenger market recovery does not automatically imply socially inclusive modal competitiveness. This framework shows where restored services remain attractive only to low-income or transport-captive users, state investment may satisfy limited welfare mobility obligations without accomplishing the broader objectives of transport diversification, revenue resilience, and substantive reduction in road dependence. The socioeconomic structure of patronage therefore becomes a critical evaluative lens for determining whether Nigeria's narrow-gauge rehabilitation represents genuine modal recovery or simply the persistence of residual rail dependency.

2.2. Theoretical Framework

This study is anchored in three theoretical perspectives: Random Utility Theory (RUT), the Transport Captivity–Choice Framework, and Transport Equity Theory. Together, these frameworks provide a robust theoretical basis for understanding why passengers with different socioeconomic profiles make different modal choices, and what those choices reveal about the social performance of Nigeria's rehabilitated narrow-gauge railway system.

2.2.1. Random Utility Theory

The foundational theoretical basis for this study is the Random Utility Theory (RUT). Originally formalised by McFadden [22] and subsequently extended through discrete choice modelling. RUT posits that rational individuals, when confronted with a finite set of transport alternatives select the option that maximises their perceived utility. Utility in this context is understood as a combined effect of the observable attributes of each mode. These include travel time, cost, comfort, and reliability, alongside the unobservable preferences of the individual traveller. Because a portion of the utility function remains unobservable to the researcher, the model is expressed probabilistically: the probability that an individual selects a given mode is a function of the relative utilities of all available alternatives. Non uniformity in utility perception is a heterogeneity perception useful in binary logistic regression modelling through estimated odds ratios associated with each socioeconomic predictor. The utility of the rehabilitated narrow gauge railway service versus the utility of intercity road travel determines the mode choice taken by passengers, The utility derived by the different socio-economic then determines choice of travel.

2.2.2. Transport Captivity–Choice Framework

A second theoretical strand informing this study is the distinction between captive and choice transit riders, a conceptual framework that has significant implications for evaluating the social performance of public transport systems. As Guerra [17] and [4] established, choice riders are passengers who have access to multiple transport options, including private vehicles, but deliberately select public transport for specific trips. Captive riders, by contrast, are those whose modal choice is constrained by limited financial resources, lack of vehicle access, or the absence of viable alternatives.

This framework is directly relevant to the Nigerian narrow-gauge context. If current railway patronage is dominated by captive riders, that is, passengers who use rail not because it maximises their utility but because it provides the cheapest means of travel relative to road transport. This implies if these passengers are classified as financially inaccessible or impractical, then the surge in ridership documented after rehabilitation may reflect residual dependency rather than genuine modal recovery. Conversely, if higher-income passengers and those with vehicle access are also choosing rail, this would suggest that the service has developed sufficient attributes to compete on utility grounds with road transport.

The central empirical question this study addresses is whether the rehabilitation programme has been sufficiently transformative to also attract choice riders, passengers who could access road alternatives but perceive rail as offering superior utility for intercity travel.

2.2.3. Transport Equity Theory

The third theoretical pillar of this study rests on the Transport Equity Theory, which evaluates mobility systems not only on efficiency or aggregate ridership metrics but on the distribution of mobility opportunities across social groups. Transport equity scholarship, represented by foundational works from [20] and [21] among other recent contributions, argues that public transport systems should be assessed by the extent to which they provide socially inclusive access to mobility across income classes, genders, occupational groups, and household types.

A transport system that serves only the poorest or most mobility-constrained segments of the population, however efficiently, is failing its equity mandate because it reinforces rather than reduces social stratification. When a mode becomes associated exclusively with disadvantaged or captive users, it enters a pattern of declining social status, reduced commercial viability, and diminished political support for sustained investments. This is dynamic well documented in transport social exclusion literature [20]; [21]. This cycle is synonymous with the previous moribund service of Nigeria Railway Corporation (NRC) that led to government intervention policy. Failure of the rehabilitated NRC services to reach beyond captive, operators will likely lose social prestige, commercial viability, and the political support needed to attract sustained investment. The theory posits

such residual transport systems tend to become trapped in a cycle of underinvestment, declining service quality, and further concentration of disadvantaged users.

2.3. Empirical Review

A review of literature from both developed and developing economies reveals important variations in the socioeconomic dynamics of railway patronage and modal choice behaviour. In developed economies of the Global North, scholarly attention has increasingly shifted from purely infrastructural and operational concerns toward broader behavioural and socioeconomic explanations of rail use. This transition reflects a growing recognition that passenger decisions are influenced not only by transport supply characteristics such as speed, accessibility, and punctuality, but also by social status, environmental consciousness, travel attitudes, and perceptions of service quality. Consequently, contemporary railway studies increasingly adopt integrated behavioral frameworks that combine economic, psychological, and sociological determinants of travel behaviour.

Within this context, income has consistently emerged as a major determinant of rail patronage among these countries. For example, [17] found significant variation in rail preferences across income groups, with higher-income passengers who have access to private vehicles, demonstrating a greater willingness to use rail services when service quality improves, while lower-income captive riders use transit regardless of service conditions. Similarly, [4], analyzed railway passengers in Great Britain and found that passenger segments differ significantly in what drives their satisfaction, with more demanding segments placing the greatest emphasis on seat comfort and train upkeep, while price sensitivity characterised less satisfied groups, suggesting that economically advantaged passengers prioritise service quality and travel experience over ticket cost. These findings suggest that service quality enhancement is central to attracting and retaining middle and high-income rail users who possess alternative mobility options.

Other recent scholarship have refined the existing traditional captive–choice rider dichotomy by identifying a third category referred to as “captive-by-choice” passengers. The work of [33] described these riders as individuals without private automobiles who nevertheless prefer public transport because of environmental values, urban lifestyles, or positive service perceptions. Extending this perspective, [24] and [8], both using post-pandemic data from Montreal, demonstrated that the proportions of captive, choice, and captive-by-choice riders have shifted considerably, and that mode satisfaction varies significantly across these groups in response to changing socioeconomic conditions and service quality. These findings underscore the dynamic nature of transport behavior and highlight the importance of empirically examining the socioeconomic composition of rail ridership rather than assuming homogeneous patronage patterns.

There are however other important socioeconomic elements identified among these countries. These variables include occupation, trip purpose, education, and automobile ownership all of which have been shown to significantly

influence rail travel behaviour. [23], analysing over 32,000 rail passenger survey responses in Great Britain, demonstrated that punctuality ranked as a significantly more important service attribute for business travellers than for leisure passengers, who placed comparatively greater weight on cost-related considerations in their travel decisions. Likewise, [30] found that highly educated passengers exhibit stronger pro-rail attitudes and greater modal loyalty. In addition, [31] found that income, job status, and transportation subsidies increase the likelihood of owning a car and driving to work, indicating that private automobile ownership reduces dependence on rail, with decisions influenced by money, time, comfort, and safety considerations, although worsening congestion and environmental concerns continue to strengthen rail competitiveness.

In contrast to the developed countries, literature from developing countries, particularly within Africa and Nigeria, remains heavily dominated by concerns relating to infrastructural deficits, operational inefficiency, affordability constraints, and service unreliability. Unlike developed economies where rail increasingly competes for discretionary riders, railway systems in many African countries continue to perform welfare and mobility support functions for economically constrained populations. Consequently, scholarly attention has focused more on infrastructure rehabilitation and operational sustainability than on behavioural dimensions of passenger choice and transport equity.

[27] examined the geometric growth and historical performance trajectory of railway transportation in Nigeria between 1970 and 2016, identifying institutional and operational constraints affecting railway development. Similarly, [27] demonstrated significant relationships between railway transport development and land-use dynamics in Nigeria, emphasizing the spatial implications of rail revitalization efforts. [18] and [2] demonstrated that affordability, accessibility, income, and educational attainment significantly influence transport preferences among Nigerian travellers. [13] explored macro-economic influence on railway ridership in Nigeria noting railway patronage as parsimonious. [1] explored socioeconomic factors of commuter railway ridership in Lagos, Nigeria, without looking into factors on the intercity path. These studies focused predominantly on urban transport systems rather than intercity rail services. Furthermore, studies on railway revitalization and infrastructure performance have paid limited attention to the behavioural determinants of rail patronage despite increasing investment in railway modernization programmes.

Consequently, there remains insufficient empirical evidence regarding how contemporary railway reforms and rehabilitation programmes are reshaping the socioeconomic profile of rail users within Nigeria's emerging conventional railway systems. Existing scholarship remains heavily concentrated on high-speed rail and urban transit systems in developed economies, with comparatively limited attention devoted to rehabilitated narrow-gauge corridors in developing countries. Without a clear understanding of the socioeconomic determinants of passenger modal choice, transport planning decisions relating to fare structures, ser-

vice differentiation, customer segmentation, and future railway investments may continue to proceed without adequate demand-side intelligence.

3. Methods

A survey research design was adopted for the study. Primary data was collected through a structured questionnaire randomly administered to 1,071 passengers traveling on the 1,132km Western Line of NRC from Lagos, Nigeria's chief commercial and industrial city in the southwest of the country, and Kano in North Central. The line was chosen because it remains the most operationally active within the network, traversing 7 states along its path. The Line, therefore, should serve a diverse socioeconomic group across multiple geopolitical zones, making it an appropriate setting for examining the socioeconomic determinants of intercity rail modal choice.

Given that the dependent variable is dichotomous, the binary logistic regression was selected as the appropriate analytical technique. The model can measure the probability of an individual belonging to one of two outcome categories being a rail or road user as a function of a set of socioeconomic predictor variables used in the study.

The dependent variable is coded as 1 for passengers who primarily use the narrow-gauge railway service and 0 for those who use road transport as their primary intercity mode. Eight socioeconomic characteristics of respondents were entered as independent variables: gender (SEX), marital status (MARIT; reference category: single), occupation (OCCUP; reference category: student), monthly income (INCOME), age (AGE), educational attainment (EDU), household size (HOUSEHOLD), and vehicle ownership status (VEH.). These variables were selected based on their established theoretical relevance in discrete choice and transport equity literature and their alignment with the socioeconomic dimensions most likely to shape utility evaluation in the Nigerian intercity railway service.

The analytical method adopted is binary logistic regression. The model in line with the theoretical framework of this study can determine the probability of choosing train travel over road travel is expressed as the odds of train use, defined as the ratio of the probability of railway use to the probability of road use:

$$\text{Odds of Train Travel} = \text{Probability of Train Travel} / \text{Probability of Road Travel}$$

The probability of train use is thus modeled as:

$$P(T_1) = 1 / (1 + e^{-(b_0 + b_1x_1 + b_2x_2)}) \quad (1)$$

Where:

b_0 is the model constant,

$b_1 \dots b_n$ are the regression coefficients for each predictor

$x_1 \dots x_n$ represent the eight socioeconomic independent variables that were used in this model.

The model coefficients are estimated using maximum likelihood estimation. The reference mode for the dependent

variable is railway travel, and all odds ratios $\text{Exp}(B)$ are interpreted relative to the baseline category of each independent variable. The binary logistic regression model was processed in IBM SPSS Statistics version 25 using the Enter method, whereby all independent variables are included simultaneously.

The analysis is presented in two stages. Block 0 evaluates the model without the inclusion of any predictor variables to establish a baseline performance level, and to identify variables most likely to contribute to the final model. Block 1 introduces all eight socioeconomic predictors simultaneously and assesses the improvement over the null baseline.

Model fit and explanatory power were evaluated using several complementary diagnostics. The Omnibus Test of Model Coefficients (Chi-Square) was used to test whether the inclusion of the independent variables produced a statistically significant improvement over the null model. The Nagelkerke R^2 , a pseudo-coefficient was reported as a measure of the proportion of variance in the dependent variable accounted for by the independent variables collectively. The Hosmer and Lemeshow goodness-of-fit test was used to assess the calibration of the model's predicted probabilities against observed outcomes, with a significance value above 0.05 indicating an acceptable fit. Overall classification accuracy was assessed through the classification table, comparing the proportion of rail users and non-users correctly predicted at both Block 0 and Block 1. Individual variable significance was evaluated at the 95% confidence level ($p \leq 0.05$), with odds ratios $\text{Exp}(B)$ reported for all predictor variables to facilitate substantive interpretation of effect sizes.

4. Result and Discussion

The result of the model fit for the logistic regression shows the overall predictive accuracy of the model improved from 67.3% under the baseline model (Block 0) to 74.8% following inclusion of the explanatory variables. This is indicative of a reasonable explanatory strength in distinguishing between rail users and non-users.

Table 1. Block 1 Classification Table (Source: Binomial Logistic Regression from SPSS 25)

	Observed	Predicted: Yes	Predicted: No	% Correct
Step 1	USE OF TRAIN – Yes	640	80	88.9%
	USE OF TRAIN – No	190	160	45.7%
	Overall Percentage			74.8%

A statistically significant improvement over the null specification ($\chi^2 = 24.273$, $p = 0.042$) and demonstrated acceptable goodness-of-fit (Hosmer–Lemeshow $p = 0.831$) confirms the model is reliable and fit for modeling travel

choice among passengers using the service. However, the moderate explanatory capacity of the model, where the combined effect of all independent variables on the dependent appears moderate. The result shows the Nagelkerke $R^2 = 0.283$ suggest variables entered into the model accounts for just 28.3% of the choice factors influencing railway usage. The remaining 71.7% can be attributed to factors that have not been input into the model.

Table 2. Block 1 Model Test Parameters (Source: Binomial Logistic Regression from SPSS 25)

Test	Statistic	df	Sig.
Omnibus Test of Model Coefficients (Chi-Square)	24.273	14	0.042
-2 Log Likelihood	110.998	—	—
Cox & Snell R^2	0.203	—	—
Nagelkerke R^2	0.283	—	—
Hosmer and Lemeshow Test (Chi-Square)	3.538	7	0.831

Within the framework of Random Utility Theory, the findings suggest that passengers evaluate rail and road alternatives based on perceived utility maximisation rather than infrastructure availability alone. The significance of gender, marital status, and income indicates that the utility derived from rail travel is socially differentiated across passenger categories. Female passengers were significantly more likely to use rail than male travellers ($\text{Exp}(B) = 2.803$, $p = 0.044$), implying that women may associate greater utility with railways relative to road transport. This outcome aligns with [29] that found that women have distinct safety and security needs in transit environments, frequently adjusting their travel behaviour and modal choices to avoid environments perceived as threatening. Within the Nigerian intercity context, where road transport is often characterised by congestion, driver aggression, and insecurity concerns, rail may represent a comparatively safer and more predictable mobility option for female passengers.

Marital status of passengers equally emerged as a significant predictor of intercity rail choice. Married respondents were substantially less likely to use narrow gauge rail service relative to single passengers ($\text{Exp}(B) = 0.049$, $p = 0.046$), indicating that household structure exerts important influence on modal behaviour. This finding supports evidence from [15], who demonstrated through longitudinal analysis of couple households that life events and household structure significantly alter travel behaviour and modal choices, independently of income or age, with married individuals particularly constrained by domestic and family-related mobility obligations. From a Random Utility perspective, the operational limitations of the rehabilitated narrow-gauge system, particularly prolonged journey duration, limited schedule flexibility, and constrained service frequency, may reduce its comparative utility for married travellers whose

mobility decisions may be tightly conditioned by temporal coordination and dependent-related travel obligations.

Income emerged as the strongest positive predictor of rail use ($\text{Exp}(B) = 2.021$, $p = 0.023$), with higher income, passengers are approximately twice as likely to choose the rehabilitated narrow-gauge railway service. This finding is analytically important as it departs from the longstanding residual perception of Nigeria's rail transport as a mobility option for lower-income travellers. Interpreted through the lens of the Transport Captivity–Choice Framework, the result suggests that the surge in passenger traffic on narrow-gauge service cannot be explained exclusively by transport captivity. Rather, the rehabilitated service appears capable of attracting at least a segment of discretionary users who possess alternative modal options. Nonetheless, these may perceive rail as comparatively advantageous only under certain travel conditions. This interpretation is consistent with evidence from [3], who demonstrates that higher income passengers disproportionately utilise rail services, and that road-related costs and congestion are key factors influencing discretionary modal choices toward public transport. In the present study, the positive income effect therefore suggests that rehabilitated narrow gauge rail services may be gradually extending beyond their traditional transport captive population. An effect that might have arisen from the inclusion of brand-new coaches and the extensive train station upgrade along the rail corridor.

The findings also possess important implications within the framework of Transport Equity. Transport equity theory argues that public transport systems should distribute accessibility opportunities across socially diverse groups rather than functioning solely as residual welfare services for economically constrained users. Historically, Nigeria's narrow-gauge railway has been socially residualised as “transportation for the poor” due largely to decades of infrastructural decline, slow service, and low operational prestige. The significance of income in this study complicates that traditional narrative by indicating that the rehabilitated system may now possess sufficient attractiveness to penetrate segments of the economically mobile population. Nevertheless, the persistence of statistically differentiated patronage across gender and marital categories also suggests that the benefits remain unevenly distributed across social groups, implying that full social inclusiveness has not yet been achieved.

By contrast, age, education, occupation, household size, and vehicle ownership did not demonstrate statistically significant influence on intercity rail choice. The absence of a significant age effect suggests that rail use within the corridor is not strongly differentiated across life-cycle categories, while the non-significance of education indicates that formal educational attainment does not independently shape railway preference. Similarly, occupation failed to demonstrate stable explanatory influence, implying that employment category alone may inadequately capture the practical constraints underlying intercity modal decisions. These findings correspond with evidence from [9] and [12], whose systematic review of mobility attitudes and mode

choices revealed that service attributes and contextual factors frequently exert stronger explanatory influence on modal behaviour than demographic characteristics alone.

The non-significance of vehicle ownership is noteworthy because private vehicle access conventionally suppresses public transport dependence in many transport systems. Its insignificance in this study suggests that car ownership does not entirely eliminate demand for rail-based intercity movement within the corridor examined. Comparable findings have been reported by [7] in contexts where public transport retains competitive relevance despite rising automobile ownership because it offers comparative advantages for longer-distance movement, fatigue reduction, cost savings, or travel reliability. Within the Nigerian context, this may indicate that rail demand is shaped less by ownership status itself than by the comparative performance of rail and road services under prevailing operational conditions.

Table 3. Socioeconomic Predictors of Passenger Choice of Intercity Narrow Gauge Railway Service (Source: Binomial Logistic Regression from SPSS 25)

Variable	B	S.E.	Wald	df	Sig.	Ex(B)
SEX	1.031	0.511	4.067	1	0.044*	2.803
MARTAL (ref: single)			4.311	2	0.116	
MARIT. (married)	-3.013	1.512	3.970	1	0.046*	0.049
MARIT (divorced)	-2.487	1.529	2.644	1	0.104	0.083
OCCUP (ref: stdnt)			7.319	3	0.062	
OCCUP – Unemp.	1.776	0.975	3.320	1	0.068	5.908
OCCUP – Self-emp.	-0.106	0.934	0.013	1	0.910	0.900
OCCUP – Paid emp.	1.288	0.834	2.387	1	0.122	3.626
INCOME	0.703	0.310	5.139	1	0.023*	2.021
AGE	-0.051	0.371	0.019	1	0.890	0.950
EDU (ref: no edu)			5.733	4	0.220	
EDU. Primary	0.085	1.790	0.002	1	0.962	1.088
EDU Secondary	1.235	0.893	1.914	1	0.167	3.437
EDU – OND/Dip	0.474	0.658	0.520	1	0.471	1.607
EDU-BSc/HND	-0.967	0.829	1.363	1	0.243	0.380
H/HOLD SIZE	-0.128	0.364	0.123	1	0.726	0.880
VEH. OWN	-0.416	0.286	2.109	1	0.146	0.660
Constant	0.023	1.907	0.000	1	0.990	1.023

Overall, the findings suggest that intercity rail patronage on Nigeria's rehabilitated narrow-gauge corridor cannot be

explained entirely through traditional assumptions of transport captivity or low-income dependence. Rather, the results indicate the emergence of a more socially differentiated pattern of rail use in which both captive and discretionary mobility considerations interact in shaping passenger behaviour. However, the moderate explanatory power of the model equally demonstrates that substantial variation in rail choice remains attributable to non-socioeconomic service variables such as reliability, travel time, station accessibility, comfort, and operational quality. From a transport policy standpoint, this reinforces the proposition that sustainable railway revitalisation in Nigeria will depend not merely on infrastructure rehabilitation, but on the extent to which restored services generate sufficient utility, inclusiveness, and competitive attractiveness to retain socially diverse passenger groups within an overwhelmingly road oriented mobility environment.

5. Conclusions

The findings of this study indicate that passenger socioeconomic characteristics play a selective rather than a universal role in shaping narrow-gauge rail patronage. Gender, marital status, and income acting were the only statistically significant predictors.

These results suggest that narrow-gauge rail demand is socially differentiated, but only along a limited set of dimensions. The pattern also indicates that rail choice cannot be reduced to a simple socioeconomic profile and that other factors, such as service quality, affordability, reliability, station access, safety, and travel time, are likely important, possibly more important determinants of modal choice on this corridor.

The practical implication is that efforts to strengthen ridership on the narrow-gauge system should extend beyond passenger profiling to address the wider determinants of service attractiveness. Rail planning should be grounded in a passenger-centred approach that addresses both cost sensitivity and service quality that responds to the specific travel needs of key user groups. Railway policy must therefore target continuous improvement of stations and rolling stock if the desired modal shift of passengers is to cut across socio-economic groups.

This study contributes to the literature by demonstrating that, in the Nigerian intercity context, socioeconomic effects on narrow-gauge rail choice are present but limited in scope. Future research should incorporate service quality perceptions, travel time, accessibility, perceived safety, and trip purpose into a more comprehensive demand model. Comparative studies across different rail corridors, particularly on the new standard gauge lines.

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Proposal of a Methodology for Assessing the Safety of Public Passenger Transport Stops

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Abstract This article focuses on developing a methodology for evaluating the safety of stops from the perspective of passengers outside the vehicle - those boarding, alighting, or approaching the stop. However, before that, it is necessary to analyze the current regulations that deal with this issue. The methodology consists of several steps: identifying the evaluated parameters, measuring them, creating a rating scale, and scoring the stops based on field data. It is then applied in a selected area of Bratislava, covering both urban (MHD) and regional (RAD) stops, in order to verify its universality for different types of stops. The results allow for the comparison of safety levels across stops and the proposal of improvements that can contribute to more efficient, safer, and more modern public transport.

Keywords methodology, stop, terminal, safety of passengers, public transport

JEL R41

1. Introduction

This article deals with public passenger transport stops, which were initially subjected to an analysis with an emphasis on creating a methodology determining the method and frequency of their assessment.

Evaluating stops is important primarily for identifying their current condition and subsequently proposing appropriate measures and reconstruction projects to ensure that a stop is safe for all users. Based on the knowledge gained and the available literature, a procedure was proposed that should be generally valid and applicable to any type of stop. [3]

Before proposing the methodology, a review of existing methodological approaches, scientific sources, and regulations concerning the location and equipment of public transport stops in various countries was conducted, specifically in the Czech Republic, Germany, and the United States. For example, American standards classify stops into several categories, such as bus bay stops, curbside stops, and extended curbside stops that allow parking by other vehicles. This type is particularly common in San Francisco, California. The standards also discuss shelter design, the number of passengers a stop should serve before shelter installation becomes effective, and the placement of advertisements at stops. [1]

In Slovakia, the issue of public transport stop evaluation is addressed by the Technical and Operational Standards of IDS BK, which deal with the topic only superficially because they also cover vehicles, tickets, and other aspects of public transport.

Based on an appropriate methodology, suitable measures for reconstruction and modernization can be proposed, lead-

ing to an increase in the quality of services provided in a given area. This is also the objective of the proposed methodology. [3]

2. Methodology design

The work focuses on the creation of the methodology itself. First, the subject of measurement was defined, i.e., the specific stop parameters that would be evaluated at each location. Subsequently, the interval and method of checking these parameters were determined. The next step involved defining evaluation levels with a precise explanation of their meaning.

A list of stops intended for measurement was then created, and sketches of these stops were prepared. In the final stage, points were assigned to individual stops based on actual field measurements. The methodology also includes tables recording compliance or non-compliance with the specified parameters, or containing value ranges with assigned scores.

The proposed methodology must be designed to be applicable to various types of stops. Therefore, it includes a broader set of parameters to cover different stop types and levels of equipment—from less-used rural stops with low passenger volumes to heavily used transport hubs in city centers where multiple modes of transport intersect.

The final part of the work involved practical verification of the methodology through real measurements. Actual stop sketches and completed evaluation tables based on field data collection were presented. The stops were then compared with each other, and the results were processed into tables and graphs illustrating their quality levels. Comparisons were carried out both among all evaluated stops and within the

same transport mode. The contribution of the methodology lies in the clear identification of deficiencies at specific stops.

The methodology consists of three main parts:

1. Subject of measurement
2. Measurement procedure
3. Stop evaluation [3]

2.1. Subject of measurement

The subject of measurement consists of stop parameters defined in an evaluation form. This form serves for the clear recording of parameters of the stop being evaluated.

The form consists of several sections:

1. General parameters applicable to all stop groups
2. Detailed specifications for each stop separately
3. Detailed specifications for bus and trolleybus stops
4. Detailed specifications for tram stops

The template of the form is included in the appendix.

Each parameter was described to clarify its meaning. For example, the parameter “Number of traffic lanes within the terminal” was defined as the number of traffic lanes that must be crossed when transferring from one mode of transport to another. Only lanes designated for motor vehicles are counted, including bus lanes, trolleybus lanes, and properly marked taxi lanes. Bicycle lanes are not considered traffic lanes. The total number of parameters evaluated at each stop was 35. [3]

An example is the Bratislava, Zlaté Piesky stop, which is equipped with a Kassel curb and a comfortable pedestrian overpass for passengers.



Figure 1. Stop Bratislava, Zlaté Piesky.

2.2. Measurement procedure

This part of the methodology determines, based on the evaluation form, how individual parameters should be measured, by what means, and how frequently. Each parameter is described individually.

For example, the parameter “Presence of a sidewalk leading to the stop” is measured visually from the stop. The evaluator observes all directions around the stop and determines whether a sidewalk leads away from the stop in at least one direction. The uninterrupted length of the sidewalk must be at least 200 meters unless the destination (building, park, etc.)

is located closer than 200 meters. This parameter should be measured once per year. [3]

2.3. Stop evaluation

In this part of the methodology, individual stops are assigned ratings.

The evaluation is based on a scoring system shown in Table 1. If a parameter is of the YES/NO type, a YES response is generally awarded 5 points, while a NO response receives 1 point. In some cases, the scoring may be reversed depending on the specific parameter. [3]

Table 1. Stop evaluation scale

Rating level	Meaning of the Rating Level
5	Parameter fully meets requirements
4	Parameter almost fully meets requirements
3	Parameter moderately meets requirements
2	Parameter only slightly meets requirements
1	Parameter does not meet requirements at all

2.4. List of Stops and Stop Sketches

This section creates a list of stops and defines how many associated stop platforms belong to the same stop name. A visual sketch of each monitored stop is also prepared.

An example is the stop group Bratislava, Pod stanicou, where:

A = Bus

T = Trolleybus

E = Tram

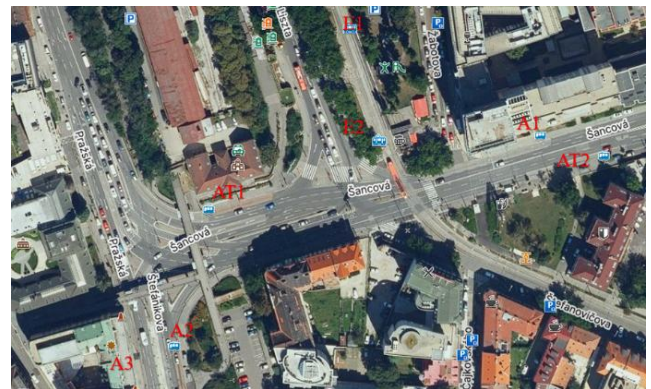


Figure 2. Sketch of stop Bratislava, Pod stanicou.

2.5. Assignment of Points to Stops

This section defines how individual parameters are scored. Each parameter is evaluated either for all stops within a stop group collectively, or separately for each stop.

For example, the parameter “Walking time for transfer within the terminal” is evaluated according to the scale in Table 2. [3]

Table 2. Walking time for transfer within the terminal

Up to 10 s	5
11 – 20 s	4
21 – 30 s	3
31 – 40 s	2
More than 40 s	1

2.6. Evaluation of measurements

The methodology concludes with the evaluation of each parameter for every monitored stop and with the comparison of multiple stops. The first step is determining importance weights. A questionnaire completed by qualified experts is recommended to establish the importance of each parameter. This approach was also used in this study.

The next step involves constructing a Saaty matrix, i.e., applying multi-criteria analysis. Each quality attribute is treated as a parameter. The most frequent questionnaire response for each parameter is entered into the matrix and used to calculate parameter weights (Table3).

Table 3. Saaty comparison scale

Number of Services	Modernization Recommendation
1-100	Slight recommendation
101-200	Recommended
201-500	Necessary
501 a viac	Highly necessary

The next step of the evaluation is the overall evaluation of the parameter, the value of which corresponds to the product of the importance weight assigned to the given parameter and the number of points allocated to the given stop. Subsequently, the overall so-called “score” of the stop was determined based on the product of these values. This evaluation was carried out for each monitored stop.

Based on the “score”, a comparison of the stops with one another was conducted. From the individual stop “scores”, the arithmetic mean was calculated, or alternatively the proportion of parameters with the worst rating, in the event that there was a parameter that significantly reduced the average stop “score”. The individual “score” values of the entire stop group from each table for each stop group were arranged from the highest value to the lowest value and were subsequently evaluated against one another in such a way that the stops with the highest “score” were considered the highest-quality stops, while, conversely, the stops with the lowest “score” were considered the lowest-quality stops.

The final step within the evaluation process is the assessment of the number of services that serve the monitored stop within a 24-hour period. This step is crucial when deciding whether or not to modernize the stop. In the event that the stop achieves 5 points, meaning that its level of safety is high, the number of services does not play a significant role in such a case. This parameter is monitored only for stops that achieved a “score” of less than 5 points. The number of services refers to the total number of all services operating on a working day in both directions for all modes of transport. The

threshold values for the number of services required for stop modernization are presented in Table 4. [3]

Table 4. Service frequency thresholds

Value	Meaning
1	Criteria are equally important
3	Slight preference
5	Strong preference
7	Very strong preference
9	Extremely strong preference

3. Results

The proposed methodology in this work was verified at 5 stops in Bratislava. The measurement procedure was carried out exactly according to the steps of the methodology. Therefore, the form was completed, a list of stops and their sketches was created, and points were assigned to the stops, as shown in the table below, where the stop Bratislava, Pod stanicou was presented as an example. The yellow section is the part of the parameters that was evaluated exclusively for bus and trolleybus stops, while the green section represents the parameters evaluated only for tram stops. The parameters are numbered according to the order in which they appear in the list of parameters in the appendix to the article.

Table 5. Number of points awarded to stop Bratislava, Pod Stanicou

Parameter	Number of points awarded					
	E1	E2	AT1	AT2	A1	A2
1	1	1	1	1	1	1
2	1	1	1	1	1	1
3	1	1	1	1	1	1
4	1	1	5	5	5	5
5	5	5	5	5	5	5
6	4	4	4	4	2	2
7	5	5	5	5	5	5
8	5	5	5	5	5	5
9	3	3	4	4	5	5
10	5	5	5	5	5	5
11	1	1	1	1	1	1
12	5	5	5	5	5	5
13	1	1	5	5	5	5
14	5	5	5	5	5	5
15	5	5	5	5	5	5
16	1	1	1	5	1	1
17	5	5	5	5	5	5
18	5	5	5	5	5	5
19	5	5	5	5	5	5
20	4	4	4	4	4	4
21	5	5	1	1	2	2
22	1	1	1	1	1	1
23	1	1	2	2	2	2
24	-	-	5	5	5	5
25	-	-	5	5	5	5
26	-	-	5	5	5	5
27	-	-	1	1	1	1

28	-	-	1	1	1	1
29	-	-	5	1	1	5
30	2	2	-	-	-	-
31	5	5	-	-	-	-
32	1	1	-	-	-	-
33	1	1	-	-	-	-
34	5	5	-	-	-	-
35	3	3	-	-	-	-

As part of the evaluation of the measurements, the method of multi-criteria analysis was used, whereby the importance weights were determined by experts, and subsequently a graph was created from them, shown below, which indicates the extent to which the individual parameters are important. The most important parameters are 10 and 14, namely “Presence of a Sidewalk Leading to the Stop” and “Pedestrian Crossing within the Terminal.”

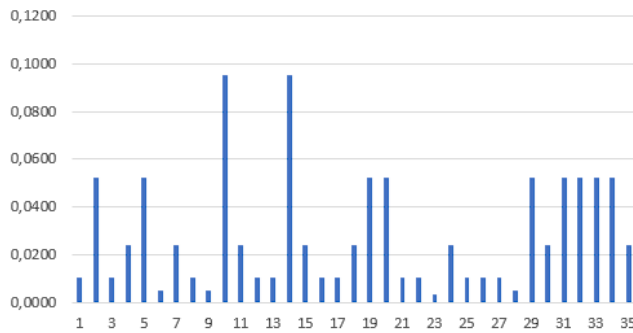


Figure 3. Importance weights of individual parameters

After multiplying the importance weights by the point value of the parameter, a point value was obtained for each parameter. These values were listed in the table 6, where, after their summation, the overall “score” of the stop is also presented (in this case, Bratislava, Pod Stanicou).

Table 6. Overall rating of stop Bratislava, Pod Stanicou.

Parameter	Váha parametra	Bodové hodnotenie parametra						Výsledné hodnotenie parametra					
		E1	E2	AT1	AT2	A1	A2	E1	E2	AT1	AT2	A1	A2
1	0,0105	1	1	1	1	1	1	0,0105	0,0105	0,0105	0,0105	0,0105	0,0105
2	0,0524	1	1	1	1	1	1	0,0524	0,0524	0,0524	0,0524	0,0524	0,0524
3	0,0105	1	1	1	1	1	1	0,0105	0,0105	0,0105	0,0105	0,0105	0,0105
4	0,0241	1	1	1	1	1	1	0,0241	0,0241	0,0241	0,0241	0,0241	0,0241
5	0,0524	5	5	5	5	5	5	0,2618	0,2618	0,2618	0,2618	0,2618	0,2618
6	0,0052	4	4	4	4	2	2	0,0208	0,0208	0,0208	0,0208	0,0104	0,0104
7	0,0241	5	5	5	5	5	5	0,1207	0,1207	0,1207	0,1207	0,1207	0,1207
8	0,0105	5	5	5	5	5	5	0,0526	0,0526	0,0526	0,0526	0,0526	0,0526
9	0,0052	3	3	4	4	4	4	0,0156	0,0156	0,0208	0,0260	0,0260	0,0260
10	0,0953	5	5	5	5	5	5	0,4765	0,4765	0,4765	0,4765	0,4765	0,4765
11	0,0241	1	1	1	1	1	1	0,0241	0,0241	0,0241	0,0241	0,0241	0,0241
12	0,0105	5	5	5	5	5	5	0,0526	0,0526	0,0526	0,0526	0,0526	0,0526
13	0,0105	1	1	5	5	5	5	0,0105	0,0105	0,0526	0,0526	0,0526	0,0526
14	0,0953	5	5	5	5	5	5	0,4765	0,4765	0,4765	0,4765	0,4765	0,4765
15	0,0241	5	5	5	5	5	5	0,1207	0,1207	0,1207	0,1207	0,1207	0,1207
16	0,0105	1	1	1	1	1	1	0,0105	0,0105	0,0526	0,0105	0,0105	0,0105
17	0,0105	5	5	5	5	5	5	0,0526	0,0526	0,0526	0,0526	0,0526	0,0526
18	0,0241	5	5	5	5	5	5	0,1207	0,1207	0,1207	0,1207	0,1207	0,1207
19	0,0524	5	5	5	5	5	5	0,2618	0,2618	0,2618	0,2618	0,2618	0,2618
20	0,0524	4	4	4	4	4	4	0,2094	0,2094	0,2094	0,2094	0,2094	0,2094
21	0,0105	5	5	1	1	2	2	0,0526	0,0526	0,0105	0,0105	0,0210	0,0210
22	0,0105	1	1	1	1	1	1	0,0105	0,0105	0,0105	0,0105	0,0105	0,0105
23	0,0032	1	1	2	2	2	2	0,0032	0,0032	0,0064	0,0064	0,0064	0,0064
24	0,0241	-	-	5	5	5	5	-	-	0,1207	0,1207	0,1207	0,1207
25	0,0105	-	-	5	5	5	5	-	-	0,0526	0,0526	0,0526	0,0526
26	0,0105	-	-	5	5	5	5	-	-	0,0526	0,0526	0,0526	0,0526
27	0,0105	-	-	1	1	1	1	-	-	0,0105	0,0105	0,0105	0,0105
28	0,0052	-	-	1	1	1	1	-	-	0,0052	0,0052	0,0052	0,0052
29	0,0524	-	-	5	5	1	1	-	-	0,2618	0,0524	0,0524	0,2618
30	0,0241	2	2	-	-	1	1	0,0483	0,0483	-	-	-	-
31	0,0524	5	5	-	-	-	-	0,2618	0,2618	-	-	-	-
32	0,0524	1	1	-	-	-	-	0,0524	0,0524	-	-	-	-
33	0,0524	1	1	-	-	-	-	0,0524	0,0524	-	-	-	-
34	0,0524	5	5	-	-	-	-	0,2618	0,2618	-	-	-	-
35	0,0241	3	3	-	-	-	-	0,0724	0,0724	-	-	-	-
SUMA								3,201	3,201	3,06	2,89	3,88	3,07

As the final step, a comparison of the stops with one another was carried out. In this case, it is a comparison of five monitored stops, namely Bratislava, Zlaté Piesky; Bratislava, Kuchajda; Bratislava, Pod Stanicou; Bratislava, Prístavný

most; and Bratislava, Súmračná. The final evaluation of these stops in comparison with one another is presented in the Figure 4. The safest stop among those monitored is Bratislava, Zlaté Piesky. On the other hand, the least safe stop is Bratislava, Súmračná. [3]

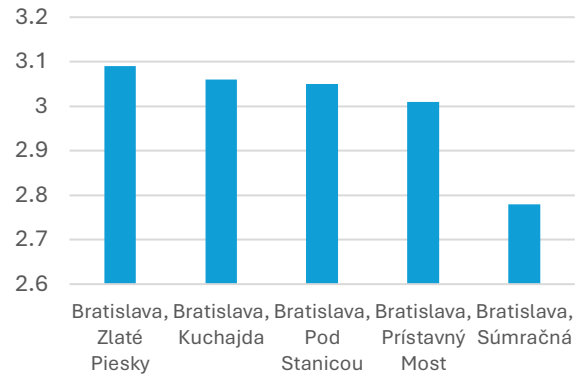


Figure 4. Mutual evaluation of stops.

4. Conclusions

The results of the study indicate that the proposed methodology for evaluating public transport stops is applicable in various types of environments and enables a systematic comparison of the qualitative level of individual stops. The practical verification of the methodology demonstrated its functionality under real field measurement conditions, while confirming that the established parameters are relevant for identifying differences between stops of different characteristics.

In comparison with existing approaches that address only selected aspects (for example, technical equipment or safety) [1], or a methodology that categorizes stops into 3 groups but does not address in greater detail the parameters associated with a stop [4], or a methodology that approaches stops only marginally and focuses on several aspects of public passenger transport [5], the proposed methodology is conceived as a universal evaluation tool, while this proposal integrates a broader set of parameters including infrastructure, passenger information, accessibility, and the overall technical condition of the stop.

A significant strength of the methodology can be considered its universality. The evaluation criteria were designed in such a way as to allow application to stops located in rural areas with a low frequency of passengers as well as to heavily used stops in city centres. The scoring system also enables simple comparison and evaluation of individual facilities.

Despite the aforementioned contributions, the research also has certain limitations. Some of the evaluated parameters may, to a certain extent, be influenced by the subjective assessment of the evaluator; however, for some parameters this cannot be avoided.

From a practical point of view, the proposed methodology may be useful as a basis for decision-making by local governments, transport operators, or road administrators when planning the reconstruction and modernization of stops. The

identification of specific deficiencies enables a more effective direction of investments and the proposal of measures where their need is the greatest.

For further research, it is recommended to apply the methodology to a larger number of stops in different regions and to verify its applicability under different transport conditions.

Based on the results, it can be concluded that the verification of the functionality of the methodology was successful. Given that this study succeeded in identifying the safest and the least safe stop, it can be concluded that the proposed methodology was correctly designed and therefore fulfills the requirement of universality.

The use of this methodology should consist of a more efficient allocation of financial resources by cities and municipalities dealing with the issue of public transport stops. The result of the evaluation of stops using the proposed methodology should determine the priority of stop reconstructions, according to which stops achieved better positions and which stops achieved worse positions. It is recommended to prioritize the reconstruction and modernization of stops that were assigned the lowest “score”, thereby ensuring an adequate level of safety at all monitored stops.

FPEDAS wishes to acknowledge all the contributors for developing and maintaining this template.

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Appendix

No.	Evaluated Parameter
1	Traffic passing by the stop
2	Walking time for transfers within the terminal
3	Need to cross a road within the terminal
4	Presence of a shelter
5	Presence of lighting
6	Platform length
7	Presence of a stop curb
8	Presence of a horizontal curve
9	Presence of a vertical curve
10	Presence of a sidewalk leading to the stop
11	Facilities for visually impaired passengers
12	Vienna-type stop
13	CCTV surveillance – audible warning system
14	Pedestrian crossing within the terminal
15	Presence of a grade-separated pedestrian crossing within the terminal
16	Number of traffic lanes within the terminal
17	Signal-controlled pedestrian crossing between stops within the terminal
18	Presence of vertical signage for the pedestrian crossing
19	Visibility of the pedestrian crossing
20	Maximum permitted speed at the stop
21	Number of traffic lanes at the stop
22	Type of stop curb
23	Number of vehicles that can fit at the stop
24	Pedestrian crossing between opposite-direction stops
25	Presence of a grade-separated pedestrian crossing between opposite-direction stops
26	Signal-controlled pedestrian crossing between opposite-direction stops
27	Walking time between opposite-direction bus/trolleybus stops
28	Traffic signal for vehicles departing from the stop
29	Type of stop location
30	Length of the field of vision when crossing between tracks
31	Presence of a pedestrian crossing between tracks
32	Presence of a grade-separated pedestrian crossing between tracks
33	Visibility obstacles at the crossing between tracks
34	Signal-controlled pedestrian crossing between tracks
35	Walking time between opposite-direction tram stops

FORMULÁR NA HODNOTENIE ZASTÁVKY

Všeobecné parametre pre celú skupinu zastávok

Sledovaný parameter	Špecifikácia parametra
Názov zastávky	
Umiestnenie zastávok	Extravilán/Intravilán
Doprava prechádzajúca okolo zastávky	vylúčená IAD/nie je vylúčená IAD
Typ zastávky podľa druhov dopravy	RAD MHD KOMBINOVANÁ
Dopravcovia obsluhujúci zastávku	
Terminál s prestupom na iné druhy dopravy	ANO/NIE
Typ terminálu z hľadiska druhov dopravy	Električka – Autobus / Električka – Trolejbus / Autobus – Trolejbus
Čas chôdze na prestup v rámci terminálu (najvzdialenejší)	
Nutnosť prechádzať cez cestu pri termináli	ANO/NIE

Bližšie špecifikácie parametrov každej zastávky zvlášť

Bližšie špecifikácie pre zastávky všetkých typov dopravy			
Sledovaný parameter	ANO/NIE	Slovné hodnotenie parametru	
Pritomnosť prístrešku	ANO/NIE		
Pritomnosť osvetlenia	ANO/NIE		
Dĺžka nástupišťa			
Pritomnosť obrubníka zastávky	ANO/NIE		
Pritomnosť smerového oblúka	ANO/NIE		
Pritomnosť výškového oblúka	ANO/NIE		
Pritomnosť chodníka na zastávku	ANO/NIE		
Vybavenie pre zrakovo postihnutých	ANO/NIE		
Viedenský typ zastávky	ANO/NIE		
Kamerový dohľad – zvuková výstraha	ANO/NIE		
Priechod pre chodcov v termináli	ANO/NIE		
Pritomnosť mimoúrovňového priechodu v termináli	ANO/NIE		
Počet jazdných pruhov v termináli			
Svetelne riad. priechod medzi v termináli	ANO/NIE		
Pritomnosť zvislého značenia priechodu	ANO NIE		
Viditeľnosť priechodu pre chodcov		1	2 3 4 5
Maximálna povolená rýchlosť pri zastávke			
Počet jazdných pruhov pri zastávke			
Typ obrubníka zastávky		KASSELSKÝ	OBYČAJNÝ
Počet vozidiel, ktoré sa zmesia na zastávku			

Pri hodnotení od 1-5 platí: 1 = najhoršie, 5 = najlepšie

Bližšie špecifikácie pre zastávky autobusov a trolejbusov

Sledovaný parameter	ANO/NIE	Slovné hodnotenie parametru	
Priechod pre chodcov medzi protifahými zastávkami	ANO/NIE		
Pritomnosť mimoúrovňového priechodu medzi protifahými zastávkami	ANO/NIE		
Svetelne riadený priechod medzi protifahými zastávkami	ANO/NIE		
Čas chôdze medzi protifahými zastávkami			
Semafor pre vozidlo vychádzajúce zo zastávky	ANO/NIE		
Typ umiestnenia zastávky		V JAZDNOM PRUHU	V ZÁLIVE

Bližšie špecifikácie pre zastávky električky

Sledovaný parameter	ANO/NIE	Slovné hodnotenie parametru	
Dĺžka zorného poľa pri prechádzaní cez priechod medzi traťami			
Priechod pre chodcov medzi traťami	ANO/NIE		
Pritomnosť mimoúrovňového priechodu medzi traťami	ANO/NIE		
Prekážky pri viditeľnosti na priechode medzi traťami	ANO/NIE		
Svetelne riadený priechod pre chodcov medzi traťami	ANO/NIE		
Čas chôdze medzi protifahými zastávkami električky			

Time-Dependent and Energy-Aware Routing in Urban Logistics

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Abstract This article examines time-dependent and energy-aware routing in urban logistics as a joint problem of routing, departure-time choice, speed-dependent energy use, and EV charging. It reviews Slovak and international literature, proposes a compact mathematical formulation, compares exact, heuristic, and adaptive solution approaches, and discusses empirical evidence from Slovak and international cases.

Keywords urban logistics, time-dependent vehicle routing, charging planning, congestion modelling

JEL R40, C61

1. Introduction

The operational problem is to serve urban customers under time windows, traffic congestion, loading constraints, and environmental or energy objectives. In a static VRP, the vehicle state is mostly location, residual capacity, and time. In a time-dependent and energy-aware urban setting, the state expands to include departure-time-dependent travel times, battery state of charge, alternative road paths whose attractiveness changes during the day, charging station choice, charging amount, and possibly station waiting time or charger capacity. This joint state space is the essential reason the problem is difficult in practice and computationally expensive in theory. [1]

Since the city, vehicle class, and fleet size are unspecified, the most defensible scholarly approach is not to hard-code a single urban archetype, but to present a parameterized formulation. In methodological terms, the same structure can model small parcel e-vans, heavier urban delivery trucks, or mixed fleets by changing battery size, charging power, capacity, and fixed vehicle cost; mixed-fleet and heterogeneous-fleet formulations in the literature explicitly support this kind of generalization. [2]

2. Literature Review

Slovak city logistics scholarship is relatively compact and strongly oriented toward governance, transferability of practical measures, and local environmental effects. Gnap and Géc define city logistics as the application of logistics principles to shipment movements in large cities through consolidation gateways, cleaner or more suitable vehicle types, and route optimization, while noting that Slovak practice has re-

lied predominantly on regulatory tools rather than integrated city-logistics systems. That observation remains analytically important because it highlights a gap between formal optimization models and actual institutional implementation in Slovak cities. [3]

A second characteristic of the Slovak literature is its applied focus on urban externalities. Beňová and Gnap's review of night-time urban goods distribution discusses congestion, emissions, and noise together, and shows that off-peak delivery can reduce route duration substantially while creating a parallel need for noise-management measures and local legal compatibility. Petro and Konečný contribute a complementary strand by treating emissions calculation as a managerial and regulatory tool for internalizing transport externalities. The Slovak standards environment has also moved toward formalized emissions reporting, with STN EN ISO 14083 providing a recognized methodological basis for quantifying greenhouse gases from transport-chain operations. [4]

A third useful Slovak contribution is the measurement infrastructure. The Žilina case study by Hrudkay and colleagues describes an urban living laboratory with 26 traffic sensors covering all nine gates of the city centre and publishing 24/7 data on counts, vehicle length classes, and speed. For research on time-dependent routing, that matters because high-frequency local traffic measurements are precisely the type of data needed to calibrate departure-time travel-time functions instead of relying on coarse averages. [5]

2.1. International Literature

International literature is deeper and more formally integrated. In time-dependent routing, a classic step was the use of FIFO-consistent travel-time functions, followed by exact branch-and-price methods for the time-dependent VRPTW and, more recently, road-network formulations that recog-

nize that the best path itself may change with departure time. Recent reviews confirm that time-dependent routing has become a mature field, but also that realism rises sharply when road-network information, multiple paths, and congestion timing are modeled explicitly. [6]

Green and energy-aware routing developed along a related line. Bektaş and Laporte's pollution-routing problem showed that emissions, fuel use, travel time, and routing should be optimized jointly, because pollution depends on speed and load rather than on distance alone. Qian and Eglese extended the logic to time-varying speeds, while Figliozzi's urban freight case-study work showed something analytically non-trivial: it is possible for route distance or duration to increase while total emissions decrease, so "shorter" is not always "greener." [7]

The EV-routing stream added battery feasibility and charging decisions. Seminal contributions include EVRPTW formulations with recharging stations, mixed EV-and-conventional fleets, heterogeneous electric fleets, partial recharge strategies, nonlinear charging functions, time-dependent waiting at charging stations, adaptive routing and recharging policies, and time-dependent EV routing models that optimize speed and departure times together. The current frontier includes exact branch-cut-and-price algorithms for time-dependent EVRP with time windows, charging-station capacity, and even overnight charging scheduling on multi-graphs. [8]

3. Analytical Synthesis

The literature divide is therefore clear. Slovak sources illuminate city access, environmental burdens, night deliveries, and the municipal data and legal structures that shape operations. International sources explain how to optimize the routing-energy-charging system itself. The research gap is not the absence of algorithms, but the lack of city-specific, institutionally implementable digital layers that connect routing models to curb access, loading zones, low-emission rules, charging availability, and public-private data governance. That is precisely the gap now being addressed in EU and OECD policy work on urban logistics, SUMPs, and logistics data sharing. [3]

4. Mathematical Models

A compact integrated formulation can be written on a directed graph $G = (N, A)$ with depot, customers, and charging stations. Let $x_{ijv} = 1$ if vehicle v travels from node i to j , T_i the service start time at node i , b_i the battery state of charge on arrival, and q_i the recharge quantity if node i is a charging station. Following FIFO time-dependent routing, travel time on arc (i, j) depends on the departure time and must preserve chronological order of departures and arrivals. [13]

$$\begin{aligned} & \tau_{ij}(t) \\ = & \text{travel time on } (i, j) \text{ when departing at time } t, \\ & t_1 \leq t_2 \Rightarrow t_1 + \tau_{ij}(t_1) \leq t_2 + \tau_{ij}(t_2). \end{aligned}$$

Time propagation with service times S_i is then

$$T_j \geq T_i + s_i + \tau_{ij}(T_i + s_i) - M(1 - x_{ijv}),$$

with customer time windows $a_i \leq T_i \leq b_i^{\max}$ for all served customers. This is the minimal mechanism that makes route feasibility depend on departure times rather than on static arc lengths.

For energy, a practical approximation used in the green-routing and TDEVRP literature expresses consumption as a function of distance, speed, and carried load. A compact form reported in the time-dependent EV-routing literature is

$$E(d, v, f) = \alpha(\mu + f)d + \beta \frac{d}{v} + \gamma d v^2,$$

where d is distance, v is speed, f is payload, μ is curb weight, and the three terms correspond respectively to a weight module, engine or auxiliary-time module, and speed module. In the cited formulation, low speeds raise the time-related term, high speeds raise the aerodynamic or speed term, and thus energy and total cost are typically convex in speed rather than monotone.

Battery balance and charging decisions can then be written as

$$b_j \leq b_i - e_{ij}(T_i, f_i)x_{ijv} + q_j + M(1 - x_{ijv}), \quad \underline{B} \leq b_i \leq \bar{B}.$$

At a charger k , total stop duration is not just charging time but

$$\theta_k = w_k(T_k) + g_k(q_k),$$

where $w_k(\cdot)$ is a time-dependent waiting or queue function and $g_k(\cdot)$ may be nonlinear or piecewise-linear, depending on charger technology and charging physics. This is where routing and charging become inseparable: even a small energy shortfall can produce a large time penalty if it triggers detour and queue exposure.

A generic objective for urban EV logistics is therefore

$$\min \sum_{(i,j),v} c_{ij}^{\text{travel}}(T_i, f_i)x_{ijv} + \sum_{(i,j),v} e_{ij}(T_i, f_i)x_{ijv} + \sum_{(i,j),v} q_k + \sum_k \omega_k w_k + \sum_i p_i L_i,$$

where travel cost, energy cost, charging price, waiting penalty, and lateness penalty are all explicit. For mixed fleets, fixed vehicle-use costs and technology-specific access constraints are added. The key analytical point is that distance minimization is only a special case of this formulation; it is generally not the correct objective in congested, electrified urban delivery.

This compact structure also clarifies why average-speed models are often too weak. Road-network studies show that the best path between two customers can change over the day, not merely the travel time on a fixed path. In parallel, green-routing studies show that energy or emissions are nonlinear in speed and load. Consequently, the route that minimizes distance, the route that minimizes travel time, and the route that minimizes energy can all differ. [9]

Table 1. Comparative view of core model families used in the literature.

Model family	Congestion representation	Energy and charging representation	Main managerial value	Main limitation
TDVRPTW on customer graph	Interval-based or piecewise FIFO travel times between customers	Usually none	Good for departure-time planning under congestion	Often assumes fixed shortest paths and ignores battery feasibility
TDVRPTW on road network	Arc-level time functions on the street network; paths can change by departure time	Usually none	Strong realism for urban navigation and access rules	Large network state space
Pollution- or green-routing models	Time-varying speeds and speed-sensitive travel cost or emission functions	Fuel or generalized energy cost; often speed/load dependent	Captures why shortest distance is not always lowest energy cost	Usually weaker on explicit EV charging
EVRPTW with recharge	Often static or simplified traffic	Battery balance, charging location, recharge amount, sometimes partial or nonlinear recharge	Good for electrification feasibility and route design	Congestion often modeled coarsely
Time-dependent EVRP / time-dependent green VRP	Joint departure-time, speed, battery, and charger decisions, sometimes with queues or station capacity	Explicit EV energy, waiting time, charging time, sometimes exact optimization	Best fit for urban e-logistics	Computationally hardest to deploy at scale

5. Solution Approaches

Exact methods remain indispensable because they tell us what “optimal” means in integrated routing-energy-charging settings. Branch-and-price was central for the classical time-dependent VRPTW, road-network exact methods extended realism further, and recent branch-cut-and-price algorithms solve time-dependent EVRP with time windows and charging decisions. Exact algorithms are particularly useful for strategic design, benchmark generation, pricing studies, and

validating heuristics on small or medium-size instances. Their weakness is well known: once time, speed, charging, and queue states are all explicit, combinatorial growth is severe. Lu and co-authors explicitly report that a commercial exact solver could handle only very small TDEVRP instances, around 15 customers, which illustrates the scaling problem clearly.

Heuristics and matheuristics dominate realistic planning horizons. Tabu search on time-dependent road networks, ALNS for time-dependent green VRP with time windows, IVNS for TDEVRP, and matheuristics for EVRP with realistic energy models all try to preserve the right physics while scaling to practical instances. In operational terms, they are the right middle ground when a fleet planner needs high-quality solutions in minutes rather than exact proofs in hours.

Table 2. Solution approaches and their operational fit

Approach	Representative methods	Best use case	Main advantage	Main drawback
Exact optimization	Branch-and-price, branch-cut-and-price, road-network exact methods	Strategic design, benchmarking, tariff and charging-infrastructure studies	Optimality guarantees and strong lower bounds	Limited scalability under rich time-energy state spaces
Matheuristics	Relax-and-fix, decomposition, route enumeration with exact subproblems	Daily planning for medium-size fleets	Strong solution quality with richer realism	Problem-specific modeling effort
Metaheuristics	Tabu search, ALNS, IVNS, hybrid local search	Large urban instances and fast replanning	Good speed-quality balance	No optimality certificate
Adaptive or rolling-horizon control	Policy-based re-routing, event-triggered re-optimization	Execution under live traffic and queue uncertainty	Operational robustness	Requires dependable data pipelines and threshold design

Adaptive and real-time methods become necessary once traffic conditions and charger queues evolve during execution. Sweda, Dolinskaya, and Klabjan develop adaptive routing and recharging policies, while urban-freight research and EU logistics-data recommendations point toward rolling-horizon dispatching supported by shared historical and real-time data. The operational logic is not to continuously re-optimize everything, but to re-plan when deviations exceed thresholds in ETA, SoC, or queue forecasts.

The Slovak evidence is especially useful for calibration. In Žilina, a living laboratory around the city centre deployed 26 lane sensors across nine gates and produced continuous traffic data with five-minute granularity. The study reports about 81.5 thousand inhabitants in the city, approximately 54 thousand vehicle entrances to the concerned area on a typical working day, and an average of 43,814 daily entries to the monitored area between September 2021 and April 2022,

with pre-Easter peaks above 64 thousand entries. For routing research, these figures matter less as fixed benchmarks than as proof that city-specific departure-time traffic profiles can be built with inexpensive municipal sensing rather than assumed from generic speed tables. [5]

International off-peak delivery evidence reinforces the same point from another angle. The Stockholm pilot study found that shifting deliveries to off-peak hours improved driving efficiency, delivery reliability, energy efficiency, and service efficiency. Slovak work reviewing Paris and other European cases similarly reports that route duration fell from about 2 hours 3 minutes to about 1 hour 37 minutes in a Paris night-delivery comparison at nearly identical distance, implying that congestion timing alone can unlock large operational benefits even before route resequencing is improved.

The policy caveat is that off-peak benefits are not “free.” Slovak and European discussions of night delivery repeatedly pair efficiency gains with the need to manage acoustic impacts, loading procedures, and neighborhood acceptability. In Slovak legal conditions, noise control remains bounded by national rules on permissible noise, infrasound, and vibration, so off-peak routing must be treated as a coordinated logistics-and-environment intervention rather than a purely algorithmic rescheduling exercise. [10]

The numbers in Table 3 are stylized rather than city-calibrated; they are intended only to show the interaction between congestion, battery feasibility, and charging, using assumptions consistent with speed/load-dependent EV-routing literature.

Table 3. Illustrative numerical example for one urban EV route.

Metric	Peak dispatch	Off-peak dispatch
Departure time	08:00	09:30
Route length	60 km	60 km
Usable energy at departure	18.0 kWh	18.0 kWh
Assumed average energy intensity	0.34 kWh/km	0.26 kWh/km
Route energy need	20.4 kWh	15.6 kWh
Mid-route charging needed	Yes, 2.4 kWh	No
Charging penalty assumed	3 min charging + 15 min detour/queue = 18 min	0 min
Pure driving time	3 h 45 min	2 h 30 min
Total route time with 40 min service	4 h 43 min	3 h 10 min

The analytical lesson from the example is important. The energy gap between the two scenarios is only 4.8 kWh, but the operational time gap is much larger because a modest battery deficit can force a charging stop whose dominant cost is not the electricity itself but detour, plug-in, and queue time. That mechanism is exactly why time-dependent congestion and charging planning should be solved together rather than in separate modules. This logic also generalizes well across unspecified urban settings: the more congested the city core

and the thinner the public charging network, the stronger the coupling becomes.

7. Implementation Challenges and Recommendations

The first implementation challenge is data architecture. The European Commission’s urban-logistics recommendations note that freight data are crucial for decision making and that both public and private sectors benefit from data sharing, but they also stress barriers of trust, security, cost, and uneven IT capacity. The same document recommends purpose-driven sharing, interoperable tools, and the digitalization of regulations, parking, charging facilities, and urban assets, rather than building isolated local platforms from scratch. For routing practice, that implies that the relevant bottleneck is often not solver quality but missing access to curb, charger, and regulation data in usable digital form.

The second challenge is regulatory fragmentation. OECD work on urban logistics hubs observes that delivery times, vehicle specifications, and access conditions vary heavily by location and that fragmented rules complicate compliance and route optimization; it also argues that restrictions should be made easily accessible online so they can be integrated into navigation systems. Slovak city-logistics writing reached a similar conclusion earlier from a national perspective, arguing that predominantly regulatory practice without harmonized information access weakens operational efficiency. The tension is structural: cities want context-specific policy, while operators want predictability and interoperability.

The third challenge is charging infrastructure and queue uncertainty. Recent EV-routing research shows that charger capacity and time-dependent waiting can change route feasibility, not merely route cost. At the policy level, AFIR is now applicable across the EU and requires Member States to ensure charging infrastructure for heavy-duty vehicles in urban nodes and safe, secure parking areas, while also setting broader coverage and user-information obligations. In Slovakia, public charging infrastructure has expanded from 2,424 publicly accessible charging points in 967 locations at the end of 2024 to 2,818 points in 1,117 locations by July 2025, which is meaningful progress but still implies ongoing deployment pressure if urban commercial fleets electrify at scale. [11]

The fourth challenge is governance integration. The revised TEN-T framework strengthens the role of 431 urban nodes and requires them to adopt Sustainable Urban Mobility Plans and report indicators, while the Commission’s urban-mobility framework explicitly includes zero-emission urban logistics and last-mile deliveries among policy priorities. This is important because freight routing should not be treated as a stand-alone optimization problem; it should be embedded in city planning that also includes congestion, noise, GHG emissions, accessibility, and land use. OECD makes the same point from a governance perspective, emphasizing that authorities should understand freight better,

define sustainability outcomes clearly, and facilitate collaboration while leaving day-to-day logistics management largely to operators

From these constraints, several practical recommendations follow. First, cities should create a freight-specific digital layer inside SUMP or SUDP practice, including curb rules, loading windows, charger status, and vehicle-access regulations, because routing quality cannot exceed the quality of these input data. Second, operators should adopt rolling-horizon dispatch with event triggers based on ETA drift, SoC deviation, and charger-queue anomalies instead of relying on one-shot morning optimization. Third, public charging strategy should prioritize depot and urban-node reliability before treating public fast charging as a universal substitute for planned energy management. Fourth, off-peak delivery should be used selectively in corridors or districts where acoustic compatibility, equipment standards, and local regulation make it socially feasible. Fifth, emissions accounting should be standardized using ISO 14083-compatible methods, preferably with GLEC-aligned implementation, so that routing, procurement, and policy evaluation use a common carbon logic. [12]

7. Conclusions

Time-dependent and energy-aware urban routing is best understood as a joint optimization problem over route sequence, departure time, road path, speed-dependent energy use, and charging decisions. The literature shows that ignoring congestion produces poor ETA estimates, ignoring energy nonlinearity produces poor environmental results, and ignoring charging queues or capacity produces infeasible or brittle EV plans. Slovak research contributes the crucial institutional and measurement perspective—city rules, environmental trade-offs, night-delivery constraints, and local traffic sensing—while international research contributes richer optimization theory and algorithms. The strongest practical architecture for unspecified urban settings is therefore hybrid: exact models for design and validation, advanced heuristics for planning, and rolling-horizon adaptive control for execution.

For scholarly and operational purposes, the main policy implication is equally clear. Urban logistics decarbonization is not just a matter of buying EVs; it requires synchronized changes in municipal data governance, charger deployment, access regulation, quiet-delivery policy, and standardized carbon accounting. Where those layers are absent, even sophisticated routing models remain underimplemented. Where they are present, time-dependent and energy-aware routing becomes a realistic instrument for cleaner, more reliable, and more governable urban freight systems.

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