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Article

Smart and Resilient Mobility Services Platform for Managing Traffic Disruptive Events

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Abstract This article aims to develop a smart mobility solution to enhance the travel experience of individuals facing traffic disruptive events. Unlike prior research focusing on isolated solutions for managing these events, this study takes a holistic approach combining real-time monitoring, predictive modeling, route guidance, and effective communication to create efficient traffic disruption management. The study introduces the Smart and Resilient Mobility Services Platform (SRMS), specifically designed to address mobility restrictions as a form of disruptive events in the Palestinian territories, West Bank. SRMS empowers users to make well-informed decisions by providing services such as real-time mapping of mobility restrictions, a prompt notification system, informal route mapping, and alternative path suggestions. Moreover, it aims to enhance engagement among travelers and citizens by adopting spatial crowdsourcing as the primary data source for potential restrictions and embracing the User-Centered Design (UCD) approach to enrich users' interaction with the developed solution. The methodology involves presenting the architectural layering system of the SRMS platform, and detailing the prototyping and design development considering the UCD approach. Results present the practical implementation of the SRMS tailored to the Palestinian context and adopted UCD.

Keywords mobility; restrictions; disruption; SRMS; spatial crowdsourcing; mapping; UCD; ArcGIS

1. Introduction

This paper presents a comprehensive framework for holistically managing traffic disruptive events. Traffic disruptive events such as natural disasters like floods, earthquakes, and wildfires, as well as man-made events such as traffic crashes, construction projects, and checkpoints have cascading significant effects [1]; for example, they cause non-recurrent traffic congestion, leading to delays and longer waiting times [2]. This, in turn, can result in higher travel costs as individuals spend more time and resources to reach their destinations [3].

Studies have demonstrated that traffic disruptive events adversely impact the economic productivity of individuals and society as a whole. For example, the heavy rain disaster in Hiroshima in 2018 cost a monetary loss of six billion JPY due to an increase in travel time resulting from route detours [4]. Kurth et al. [5] highlighted the impact of random disruptive events on the road network on the gross domestic product (GDP) in different cities in the USA. For example, in San Francisco, when a traffic disruption occurred on just 3% of road segments, travel time increased by 34%, leading to a notable 6.64% decrease in GDP.

Traffic disruptions pose obstacles to long-term social sustainability. Waiting times and delays exert adverse effects on both drivers and passengers, presenting heightened stress and increased frustration [6,7]. The road closure occurred due to specific traffic events such as traffic crashes, earthquakes, debris falls, etc., undermines the humanitarian emergency supply and evacuation process [8].

Furthermore, the delays in travel, waiting times, and travel detours resulting from traffic disruptions lead to adverse environmental implications, presented in increased fuel consumption and air pollution. An experiment conducted by the Beijing Jiaotong University aimed to examine the impact of frequent starting and stopping on fuel consumption and vehicle exhaust emissions. The results demonstrated that fine particulate matter $PM_{2.5}$ emissions from idling cars were five times higher under congested conditions. Furthermore, investigations into pollution sources revealed that motor vehicle emissions contribute to 31% of the total local pollution emissions, with emissions under congested conditions being 50% higher compared to normal traffic scenarios [9].

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The previous socioeconomic and environmental consequences of traffic disruptions have catalyzed scholars to develop innovative strategies for managing these disruptions. These strategies harness smart enabling technologies and advancements in information and communication technology (ICT) [10]. For example, scholars commonly focus on developing real-time monitoring and data collection for road traffic to automate road defect and anomaly detection (ARDAD) [11], and the development of traffic simulation and visualization platforms [12].

Some researchers developed predictive models using historical and real-time traffic data to forecast potential disruptions and events [6]. For example, Aljuaydi et al. [13] developed machine learning-based prediction models such as convolutional neural networks (CNN), and long short-term memory (LSTM) to forecast traffic flow during road crashes and rainy conditions. Others have mined the traffic data from social network services and employed machine learning and natural language processing (NLP) to construct prediction models for traffic event detection [14] and traffic flow predictions [15]. For example, Salazar-Carrillo et al. [16] proposed a methodology to geocode traffic-related events gathered from Twitter, constructing a model that produces spatiotemporal information about traffic congestions via spatiotemporal analysis.

Another focus area involves the development of dynamic route guidance and navigation systems to offer commuters optimal route choices during disruptive events. These systems consider current traffic conditions, road closures, and congestion to suggest alternative routes that help drivers avoid areas with disruptions, minimize travel time, and enhance user safety. For example, Alkhabbas et al. [17] introduced the ROUTE framework, which supports multimodal planning, considering traveler preferences and responding to city-specific constraints set by authorities. Other scholars utilized geospatial technologies in managing disruptive events, employing them for traffic risk mapping, hotspot analysis [18], and emergency route planning [19]. For example, Audu et al. [20] established a digital road network database to facilitate rapid emergency responses to road traffic accidents in Nigeria utilizing ArcGIS capabilities.

From the previous literature, the existing strategies for managing disruptive events often address specific challenges in isolation, leading to fragmented approaches. For example, certain researchers concentrate on creating systems to detect events and send out early notifications. Meanwhile, others develop route guidance and travel planning platforms that take context into account, aiding users in discovering alternate routes during or after such events. Additionally, some scholars employ geospatial technologies and map-based platforms to map and visualize data. This disjointed approach can result in suboptimal solutions that fail to comprehensively address the complex nature of traffic disruption management.

Another observation is the limited involvement of citizens in the development of smart solutions, which has the potential to enhance the acceptance and effectiveness of these solutions [21]. To bridge this gap, some researchers have proposed integrating crowdsourcing technology as a supplementary data collection method for traffic management. For example, Crowd-IoT combines crowdsourced data with the Internet of Things (IoT) [22], while others explore the combination of deep learning and blockchain to empower spatial crowdsourcing, known as DB-SCS [23]. Despite these efforts, there's still a gap in creating comprehensive smart mobility solutions that effectively leverage spatial crowdsourcing as a primary data source.

This study aims to fill the observed gaps by developing a holistic smart solution to manage traffic disruptive events. It combines real-time monitoring, predictive modeling, route guidance, and effective communication to create efficient traffic disruption management. Moreover, it aims to enhance travelers' and citizens' engagement by adopting spatial crowdsourcing as the primary data source for potential events and considering the User-centered Design (UCD) approach to enhance the users' experience with the developed solution.

The study introduces a design framework for the Smart and Resilient Mobility Services platform (SRMS). This framework was tailored to address mobility restrictions in the Palestinian territories, specifically the West Bank. SRMS platform aims to empower travelers to make informed decisions, optimizing their travel expenses in both time and money, ultimately enhancing their overall travel experience.

These restrictions started around thirty years ago with the installation of checkpoints [24,25], the separation wall [24], and settlers-related violent incidents [26]. According to a recent survey conducted by the Office for the Coordination of Humanitarian Affairs (OCHA), there are approximately 593 movement obstacles in the West Bank. Among these obstacles, 26% are road gates, 30% are checkpoints, and the remaining 54% are earth mounds, roadblocks, road barriers, and other types of barriers [27].

The impact of these mobility restrictions extends across social, economic, and environmental spheres, significantly affecting the traveling experience and undermining sustainability drivers [28]. Economically, they have led to increased costs, heightened uncertainty, and reduced employment opportunities, working days, and wages [29]. Socially, these restrictions disrupt the social fabric of Palestinian communities, limiting cultural exchange [30], and contributing to long queues, and arbitrary rule implementation, which negatively impact daily life and well-being [31,32]. Additionally, incidents of violence perpetrated by settlers against travelers have further destabilized the prospects for a peaceful and just society [33].

From an environmental standpoint, these mobility restrictions have markedly increased travel time, energy consumption, and CO_2 emissions. The prolonged travel time caused by checkpoints can be up to 27 times, notably elevating energy consumption and CO_2 emissions. Estimates suggest an increase of 275% for gasoline vehicles and 358% for diesel vehicles [34].

2. Materials and Methods

This section presents the methodology for creating the SRMS platform framework. It starts by (i) presenting the architectural layering system of the SRMS platform, and (ii) detailing the prototyping and design development, which takes into account user engagement and utilizes a user-centered design approach.

2.1. Architecture of the SRMS Platform

This phase concerns defining the architectural model of the SRMS platform. SRMS, as a novel smart solution to address the mobility restrictions challenges, follows the concept of smart city architecture layers [35,36]. SRMS is composed of four layers: urban mobility infrastructure, data collection and transmission, data processing layer, and services layers, as depicted in Figure 1.

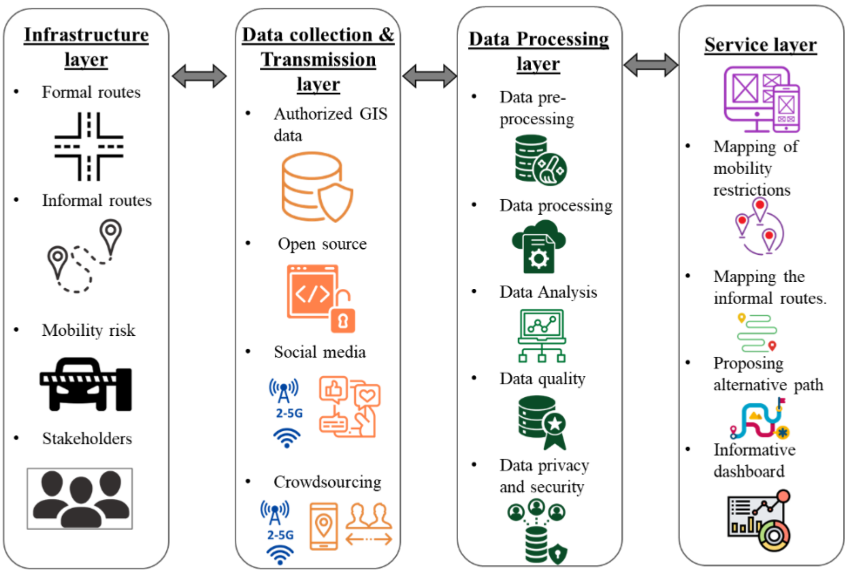

Figure 1. The architecture of smart and resilient mobility services platform (SRMS).

2.1.1. First Layer: Urban Mobility Infrastructure

The first layer in the SRMS system is the infrastructure of the urban mobility system. It is the foundation for designing a resilient and smart mobility service. It constitutes the data source in the smart system [35]. This layer includes (i) formal interurban routes, (ii) informal routes, (iii) mobility risk, and (iv) stakeholders involved in the SRMS.

i. Formal Interurban Routes

The formal interurban routes concern routes used by interurban travelers. They are characterized by short travel time and high speed, making them suitable for interurban mobility. Due to high traffic volume and high traveling speed, formal routes have increased exposure to disruptive risks such as traffic crashes [37], hazardous material accidents [38], and natural disaster consequences [2]. Hence, the formal routes require regular monitoring and maintenance to avoid failure in providing mobility service, which entails massive traffic interruption, traffic congestion, and physical and human loss [39].

The role of the formal route in creating a smart and resilient mobility system includes (i) forming the base map of the SRMS that acts as a reference for all SRMS services, including real-time reporting and suggesting alternative paths, and (ii) publishing and updating the formal routes database via the SRMS platform that helps transport authorities in infrastructure management and minimizes failures and prevents disruptions that could lead to traffic interruptions and congestion.

ii. Informal Routes

The informal routes emerge in mobility systems subjected to physical or natural hazards, leading to blockage in the main roads and traffic congestion. They emerge based on local knowledge, community preferences, and evolving transportation patterns. Informal routes have significant roles in the SRMS platform, including (i) providing flexible and adaptable mobility patterns—unlike formal routes, informal routes may consist of various paths and passages that are not officially designated for transportation purposes; (ii) enhancing the community resilience [40], which takes different shapes depending on the community context and available resources [41,42].

While existing literature on urban mobility resilience focused on engineering perspectives [43,44], the experience of travelers dealing with road restrictions and traffic interruptions, especially in conflict areas, has not been widely addressed [45,46]. Introducing informal routes into the urban mobility system offers a novel perspective for enhancing resilience.

iii. Mobility Restrictions

The mobility restrictions could be physical or intangible restrictions that impede people's movement. Physical mobility restrictions have different shapes, such as checkpoints, roadblocks, road gates, and violent actions. Intangible mobility restrictions could be policies prohibiting the use of certain roads. By integrating mobility risk considerations into the system, the SRMS becomes better prepared to handle disruptions and ensure the efficient and resilient operation of the urban mobility network.

Considering mobility restrictions as a component of urban mobility infrastructure has several advantages. First, there is an advantage in risk management and informed decision-making. Second, resilience enhancement is achieved by identifying the timeline of the operation mechanism of the mobility restrictions, whether they are planned, random, or conditional. Third, assessing the socio-economic and environmental impacts involves understanding these restrictions' broader effects on individuals, communities, and the environment. Lastly, it provides visual presentation and mapping within the urban mobility system. This allows for a better understanding of the spatial distribution of these restrictions and aids in decision-making processes.

iv. Stakeholders

Stakeholders include the formal and informal groups involved in a resilient mobility system. They include individuals, governmental authorities, and non-governmental organizations (NGOs). Stakeholders' involvement in developing the smart and resilient system is crucial for the success of the system [47,48].

Each stakeholder is a potential source of static and dynamic data [35]. Hence, it is necessary to ensure a well-organized data collection and sharing procedure among stakeholders and ensure data security, integrity, and access rights protection. Figure 2 shows the power-interest graph for the SRMS stakeholder. It is a common tool to map the stakeholders according to their power and interest [48]. According to Figure 2, SRMS stakeholders could be classified into three groups, including (i) high power high interest group, (ii) high power low interest group, and (iii) medium power medium interest group.

The high power high interest group includes drivers and passengers who use the interurban mobility network. They are considered mobile sensors on the road network [49]. They capture and feed the system with real-time localized data about traffic conditions and mobility restrictions, and share their experience in informal traveling using spatial crowdsourcing technology. Also, they are the primary users and beneficiaries of SRMS.

The high power lower interest group includes the governmental organizations who have power in the SRMS through providing transportation infrastructure data but do not directly benefit from the SRMS compared with the first group. The higher governmental authority, such as the Ministry of Transport, is the source of high-classified roads, including road characteristics, maintenance needs, physical condition, mapping, etc. The local governmental authority, such as the municipality, is a source for low-classified roads inside the locality.

The medium power medium interest group includes residents of localities adjacent to formal roads, and NGOs. They play the role of observers in the SRMS by reporting traffic data and mobility restrictions on the nearby formal roads. They do not have high benefits compared with the first group. Residents can provide data in the areas not accessible by travelers in the usual situation. NGOs in SRMS play the role of monitoring and describing the restrictions on the interurban road network, their categories, functioning mechanisms, mapping, etc.

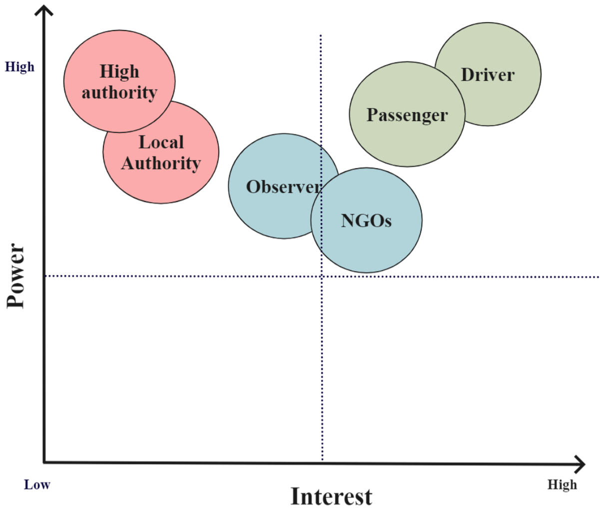

Figure 2. Power–Interest graph for SRMS stakeholders.

2.1.2. Second Layer: Data Collection and Transmission

This section concerns the following questions: (i) what are the available data sources for the SRMS services, (ii) what are the types of obtained data, (iii) what are the data formats, (iv) what are the methods observed for capturing and gathering these data, and (v) how the captured data will be transmitted to the SRMS processing layer.

Data is the core of the SRMS, as all the decisions are based on the analysis of the collected and captured data from the mobility infrastructure [36]. Data in the SRMS is captured from various sources, including high governmental authorities, local authorities, NGOs, and the community, as illustrated in Figure 3.

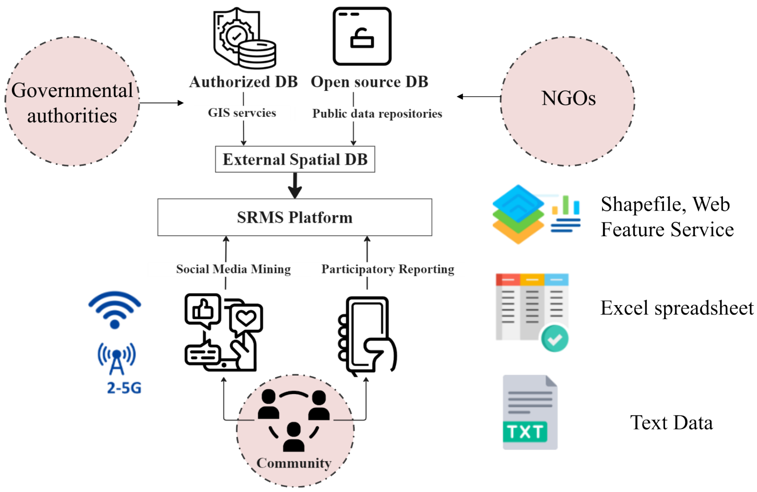

Figure 3. Data sources and collection methods.

Figure 3 shows that data could be obtained from (i) open sources accessible by the public, (ii) authorized database that is only available for authorized people, and (iii) crowdsourcing data, which is generated by the people (crowd) through the SRMS platform and social media. The obtained data has different types, such as spatial data in the form of Esri vector data storage format (Shapefile), which is common spatial data storage that stores the location, shape, and attributes [50], feature service, mobile device GPS sensing data, tabular data, and text data. Table 1 presents the data used in the SRMS for each infrastructure category and describes the data sources, types, and formats.

Table 1. SRMS's data sources, types, and format.

Infrastructure Category	Data Source	Source Description	Data Type	Data Format
Formal routes	High governmental authority: Ministries	Authorized transportation database	GIS spatial database	Esri Shapefile: SHP, .DBF, .SHX, etc.
Informal routes	Community experience and observations	Spatial crowdsourcing	Crowdsourcing data using the GPS of mobile devices	Hosted feature layer (Feature service)
Mobility restrictions	NGOs	Open source	Descriptive textual data Tabular data	Text, Image, Excel file (.xlsx)
	Community observations	Spatial crowdsourcing	Crowdsourcing data using the GPS of mobile devices	Hosted feature layer (Feature service)
		Social media	Crowdsourcing data: processed text data	Text

Methods used to obtain the above-mentioned data are summarized in Figure 4. The authorized data is obtained through formal communication with related authorities to provide access to their GIS services using login data (ID and password). Open-source data, such as those published by NGOs, is gathered through public data repositories. These repositories often provide direct download links or APIs to access the data. The authorized and open-source data will be processed, filtered, and stored in a cloud external spatial database (ESDB).

The community provides the SRMS platform with real-time spatial data about traffic conditions, mobility restrictions, and informal routes using participatory spatial crowdsourcing (SC) [22,49,51], where users directly report on the SRMS platform. SRMS platform is integrated with Survey123 to share traffic data and enhance community resilience during mobility incidents. Figure 4 shows methods of obtaining crowdsourced data in the SRMS platform using Survey123 and API telegram.

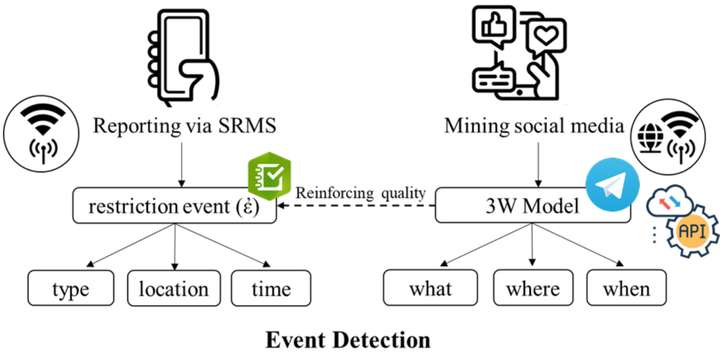

Figure 4. Methods of obtaining crowdsourced data in the SRMS platform.

ArcGIS Survey123 has confirmed its efficiency and capability in data collection, analysis, and visualization compared with other crowdsourcing applications. Jay et al. [51] compared map-based crowdsourcing applications, including Ushahidi, Maptionnaire, Survey123, Open Data Kit, and GIS Cloud, considering categories such as data input, management, analysis, visualization, and costs. The study revealed that Survey123 is the only platform offering web and mobile applications that support both Android and iOS devices. Also, Survey123 has superiority over other applications in providing a built-in database, supports the removal and editing of single data entries, sorting and filtering, and many supported format options. Additionally, Survey123 provides high visualization options compared with other crowdsourcing applications.

The second method for collecting data from the community is using social media [16]. The community provides near real-time data regarding traffic conditions and restrictions using the Telegram platform. Telegram provides the feature of pure instant messaging, which will feed the SRMS system with accurate updated data. Furthermore, mining the Telegram data as a source of mobility restrictions data is a novel approach in social media mining studies [52]. So, the mobility restrictions and road traffic data were extracted from Telegram channels and public groups using Telegram API [53,54]. Telegram API allows programmatically interacting with Telegram data and services and benefits from many functionalities.

SRMS applies data retrieving techniques to gather people's observations at each specific time interval, and with NLP techniques, the insights and useful information will be extracted [13,55]. Following capturing data from its sources, data will be transferred to the processing cloud ArcGIS server through the transmission layer. Data transmission from the community is based mainly on a mobile connection. Data transmission from other sources will be based on the internet connection.

2.1.3. Third Layer: Data Processing and Analysis

This layer concerns processing and storing the collected data to generate a mobility service decision. Data processing and analysis were applied using one of the Web-GIS advancements, ArcGIS Online. Choosing ArcGIS Online as a platform service stands for several factors, including (i) it provides scalable and flexible computing resources [56]; (ii) users can access their maps and data from anywhere with an internet connection [57]; (iii) it provides the capability of streamlining the application development and deployment; (iv) it allows utilizing application templates, access to hosted APIs and software development kit components, and connection to shared widgets and add-ins [56].

The processing layer is composed of four components that communicate with each other to provide a suitable mobility service, including (i) data pre-processing; (ii) data processing; (iii) crowd-context database; and (iv) privacy and security control as illustrated in Figure 5.

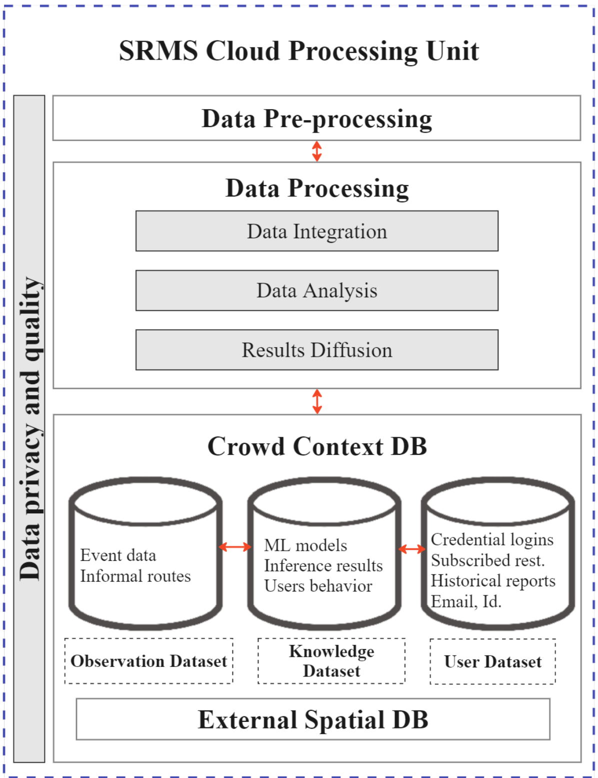

Figure 5. Data processing components in SRMS.

i. Data Pre-processing

This phase concerns data cleaning. One of the SRMS platform challenges is the heterogeneity of data sources. The system relies on various data sources (social media, mobile devices, open sources, etc.), which could include noises (duplicate data, data with transmission errors, incomplete data, etc.). For data homogenization, it is proposed to remove data noises through a middleware platform between the transmission and processing layer [21] that maintains the collaboration among different data sources [21,22,58]. The Pre-processing phase uses a combination of automated and manual methods to clean and filter the data. For example, it removes outliers, detects and corrects errors in GPS coordinates, and removes duplicate reports.

ii. Data Processing

This concerns processing and analyzing the pre-processed data through various mathematical analyses and machine learning algorithms to provide mobility services. The data processing includes data integration, data analysis, and results diffusion.

a. Data Integration

This phase concerns extracting and transforming the pre-processed data from a large crowd into an internal data structure as raw data stored in a conventional database. For example, the social media content will be processed using NLP and text analysis techniques [55,59] to integrate with the data reported via SRMS; this will reinforce the data quality.

b. Data Analysis

This component plays a significant role in providing SRMS mobility services through conducting mathematical and artificial intelligence tools to extract the main features of collected data, ensure data quality, and develop predictive models and alternative routes in response to the mobility system's real-time context. For example, real-time mapping of mobility restrictions will be provided by analyzing the crowdsourced GPS data using ArcGIS Online capabilities to extract insights about mobility restrictions and traffic conditions. The telegram data will be analyzed using NLP processing and analysis techniques, including tokenization, removing stop words, regular expression (regex), and geocoding.

By leveraging historical data, real-time reports, and factors like time of day and day of the week, the system can predict waiting times at mobility restrictions using Random Forest Regression (RF) [60]. When the SRMS detects significant delays at a particular restriction, it could suggest alternative routes to users, helping them avoid congested areas. Additionally, the application employs the shortest-path algorithm, Dijkstra's algorithm, to determine the optimal route based on criteria such as time, distance, or safety.

Within the data analysis process, an essential aspect involves collaborating with the data quality manager to manage the quality of reported data. Since SRMS relies on user-reported data, there is a possibility of encountering low-quality data due to intentional or unintentional system misuse. Detecting such low-quality data can be challenging during the pre-processing and processing phases. To address this issue, data analysis conducts a final quality check on the reported data before storing it in the crowd context database. This is achieved by implementing data quality management protocols, which will be elaborated upon in a subsequent section. Figure 6 presents the data analysis techniques in the SRMS analysis layer.

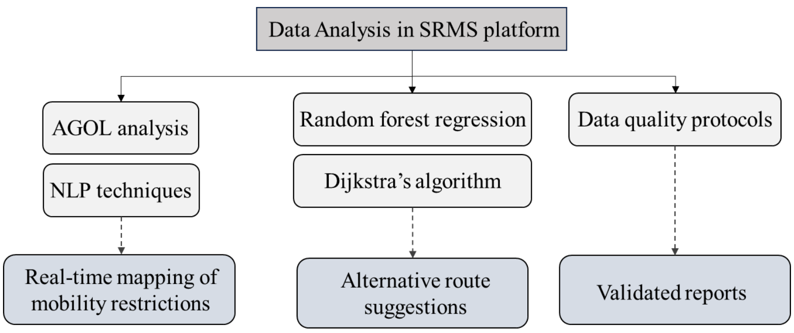

Figure 6. Data analysis techniques in the SRMS Platform.

c. Results Diffusion

This component concerns preparing the processed results of previously explained computational analysis to be classified and stored in the crowd context database. Integrating the results with the crowd context database will facilitate their transmission to the service layer.

iii. Crowd Context Database (CCDB)

CCDB plays a crucial role in delivering various SRMS services. The data within CCDB is securely stored and processed to ensure the privacy, accuracy, and reliability of information provided to users [61].

Data stored in the crowd context database contains both structured and unstructured data, as illustrated in Figure 7. Structured data, originating from user-generated content, includes information such as the location of informal routes and mobility restrictions, the type of restriction, the time of reporting, the user's login credentials, emails, etc. User-generated data is stored in the observation dataset and the user dataset, which consists of different tables representing specific types of information, with each field holding relevant data [49].

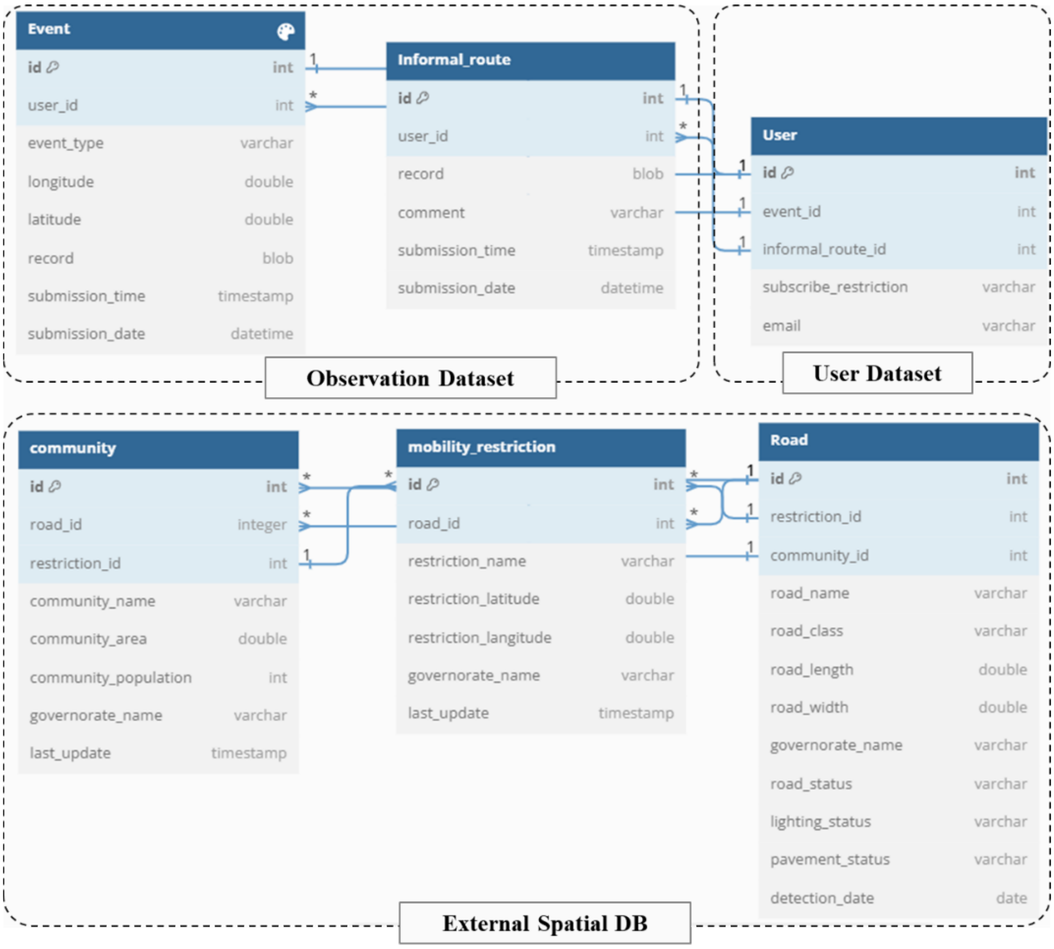

Figure 7. The structured data and their corresponding schema within the crowd-context database.

The observation dataset contains two tables: the event table and the informal route table. The event table has a set of fields that describe the event reported by the platform's users, such as the location of an incident, the type of incident, and the time it was reported. The informal route table has fields describing the observed route, such as route location, comments about the route, and the reporting time. These structured data help in data filtering, statistical analysis, and applying machine learning algorithms to extract insights and identify trends.

The user dataset stores user information like login credentials (username and password), user ID, email addresses, historical reported events and informal routes, and subscribed mobility restrictions. The user dataset plays a crucial role in ensuring the accuracy and reliability of shared data [62] and providing a personalized experience for users of SRMS. It enables customized features and tailored services based on individual preferences and subscribed restrictions.

Another structure data that the CCDB has is the external spatial database (ESDB). ESDB is the repository of processing and storing open source and authorized data. It contains tables describing the external environmental context, such as road networks, built-up areas, and permanent mobility restrictions. It forms the base map of the SRMS platform. The external spatial database independently processed the spatial data using GIS capabilities, including georeferencing, digitizing, classifying, converting, geoprocessing, and removing duplication and missing data. Then, the data is tabulated for fast and efficient querying and analysis. Figure 7 presents the structured data and their connections within the crowd-context database.

The unstructured data in the crowd-context database is presented in the data generated from the algorithm and models such as restriction-waiting time predictions models, social media data processed using natural language processing, and other text analysis techniques to extract valuable information about road conditions and stored in text files. The unstructured data includes the inference results from machine learning models, such as users' behavior and reliability. This data is used to improve the quality, accuracy, and performance of the SRMS services. The unstructured data will be stored in the knowledge dataset, which is crucial in the crowd context; it is the repository for long-term data in the SRMS.

2.1.4. Fourth Layer: Service/Application

The application layer plays a crucial role in providing services to users [36]. This layer presents the analyzed data from the previous layers as user-friendly and ensures the use of attractive tools to enhance user interactivity with the provided services [35]. The SRMS service layer encompasses various services that aim to ease people's mobility during disruptive events to minimize the adverse socioeconomic impacts and save lives. These services include (i) real-time mapping of mobility restrictions and traffic conditions; (ii) real-time altering system for the mobility restrictions; (iii) mapping of informal routes; and (iv) providing alternative path suggestions to optimize safety, travel time, and distance.

2.2. Prototyping and Development of SRMS Platform

This phase involves creating a prototype of the SRMS platform, encompassing software application development and interface design. Initially, the SRMS platform was developed as a mobile web application accessible via a mobile web browser. This choice was informed by a review of different comparison studies that assessed mobile web apps with native apps, hybrid apps, interpreted apps, and widget-based apps [63–66]. Considered factors included installation process, updates, app size, offline access, user experience, push notifications, development cost, security, ease of updates, implementation complexity, licensing, programming language, and discoverability.

The SRMS platform can benefit from being a mobile web app in several ways. Firstly, it offers enhanced accessibility to a wider user base, as it can be accessed on various devices without platform restrictions. Secondly, it is a cost-effective solution as it utilizes standard web technologies that are widely available such as HTML, cascading style sheets (CSS), and JavaScript, and can be used across multiple platforms, hence, reducing the need for specialized resources [63]. Thirdly, it allows for responsive development, enabling developers to quickly address user feedback and make necessary updates. This responsiveness is crucial for spatial crowdsourcing projects that require frequent modifications to meet evolving user needs [64].

Based on the literature sources [67], a comprehensive summary of the technical and non-technical considerations for native, hybrid, and web apps is presented in Table 2.

Table 2. Comparison of native, hybrid, and web apps based on technical and non-technical considerations.

Considerations	Native	Web	Hybrid
Efforts of supporting platforms and versions	High	Low	Moderate
user interface (UI)/user experience (UX)	Excellent	Moderate	Moderate
Potential Users	Limited	Maximum	Large
Development Cost	High	Low	Low
Ease of Update	Low	High	Varying
Implementation Complexity	High	Low	Moderate
Device capabilities access	Full	Partial	Full
Performance	High	High	High
Approval cycle	Mandatory	Not required	Varying
Monetization in the app store	Available	Not available	Available

To overcome limited UI and UX in web apps, the SRMS mobile web app design draws inspiration from Progressive Web Apps (PWA) principles. The app is adaptive and responsive, catering to different screen sizes and orientations. CSS are used to render different styles based on the device, ensuring a user-friendly experience. Also, the UCD approach was adopted to ensure high user interaction and acceptance.

Regarding the challenge of device capability access, the SRMS mobile web app only requires access to the device's microphone for recording audio reports and the GPS sensor. By limiting the app's access to these specific functionalities, the SRMS platform maintains a streamlined approach while still fulfilling the necessary requirements for spatial crowdsourcing activities.

2.2.1. SRMS UCD

Accepting crowdsourcing applications and user interaction depends on considering the users' needs [68]. This approach was addressed in the term UCD [69–71]. UCD, in the context of software engineering, is an approach to designing applications that prioritizes the end-users needs and limitations [72]. It involves understanding who the users are, their goals, motivations, and frustrations, and designing intuitive and easy-to-use applications that meet their needs.

The UCD was applied in SRMS using the Scenario Persona method [72]. Persona's techniques presented initially by Cooper [73] were used to create fictitious representations of target users based on the real data gathered from research. Scenarios describing interactions between systems and users were first discussed by Carroll & Rosson [74]. They can be employed to illustrate how a user might accomplish particular tasks with the system. Scenarios aim to create a realistic and relatable story that captures the user's needs, motivations, and behaviors in a specific context.

The personas techniques were applied by designing an online survey aimed to investigate information about the SRMS potential users from different perspectives [75], including (i) personal profile (age, education, profession, living and working place, etc.), (ii) commuting mode and traveling cost (travel time, travel cost, commuting frequency, mode of transport, etc.); (iii) understanding their need, preparedness, and interests concerning their interurban mobility (level of interest in application's topic compared to other topics, internet access, needs, and concerns).

Scenario techniques were applied using the same method of personas, an online survey method. The scenario techniques were developed using a set of scenario questions to measure the users' preferences for listed application features and, simultaneously, the level of the users' willingness to interact with the proposed feature. This will indicate a preference-behavior gap for the application features; the minimum gap shows high user interaction. Figure 8 depicts the methodology of applying UCD in designing the SRMS platform.

Following an understanding of the users' background, potentials, needs, concerns, and interaction scenarios with the application features, the interaction model for the SRMS design was created. The interaction model is a design model that defines how all objects and actions of an application interrelate in ways that mirror and support real-life user interactions [76]. Interaction models aim to create a clear and intuitive design that allows users to accomplish their goals efficiently and effectively.

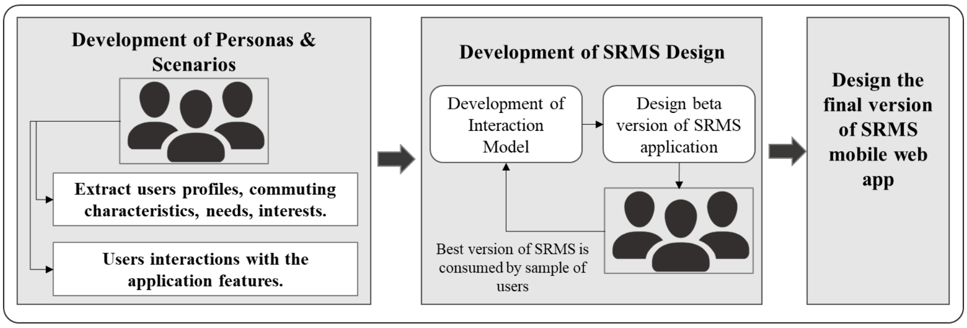

Figure 8. Methodology of creating SRMS platform design using UCD.

Interaction models can take various forms, including flowcharts, wireframes, and diagrams. They typically include information about the user's goals, the actions they can take, and the feedback they receive from the system. An interaction model was developed for the SRMS platform using Modeling Language for Interaction as a Conversation (MoLIC). MoLIC is a modeling language for the interaction between the user and the designer proposed by [77]. It represents all interaction paths, including alternative paths for the user to reach the same goal [78]. Figure 9 illustrates the MoLIC diagram for reporting checkpoint events for an SRMS-registered user.

The basic elements of the presented MoLIC diagram are the following:

- The opening point in the interaction is represented by a filled black circle, indicating where the user accesses the system.
- The scene, depicted as a rounded rectangle, represents the moment in the interaction where the user decides how the conversation should proceed. The top compartment contains the topic and the user's goal, while the second compartment contains the dialogue details, specifying whether the user (u) or the designer's deputy (d) is emitting the sign.
- User transition utterance is indicated by an arrow labeled with a user utterance indicator (u:), representing the user's intent to continue the conversation in a certain direction.
- Designer transition utterance is the response to a user utterance, typically provided after a system process. It is depicted by an arrow labeled with a designer utterance indicator (d:).
- The system process is represented by a black box and signifies the internal processing of a user request, which generates feedback to the user when different outcomes are possible.
- Breakdown recovery utterance is used to assist the user in recovering from a communication breakdown. It is depicted by a dashed directed line in the diagram, accompanied by the corresponding utterance, such as "invalid credentials" in Figure 9.

The MoLIC model was utilized to design the user's interaction with various SRMS services. Based on this model, a beta version of the SRMS mobile web app was developed and tested by a sample of users. Their feedback regarding their experience, comments, suggestions, and issues related to omissions, ambiguity, and unclear presentation was collected.

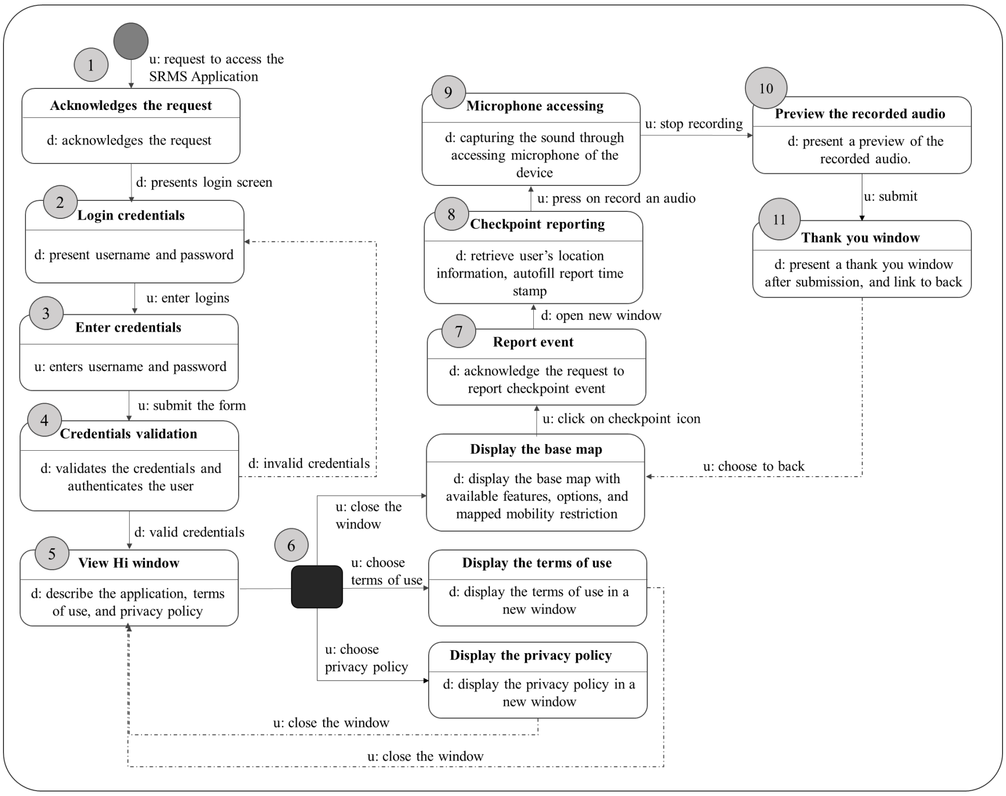

Figure 9. A MoLIC diagram for event reporting service in the SRMS platform.

3. Results and Discussions

3.1. Overview

This section shows the practical implementation of the SRMS platform in the Palestinian territories, West Bank to alleviate the negative effects of mobility restrictions and enhance the resilience of interurban mobility in the region. It will present the results derived from employing the UCD approach. Subsequently, it will showcase the practical application of the SRMS platform's mobile web app using ArcGIS Experience Builder, and illustrate the functionality of one of its services—real-time mapping of mobility restrictions.

The West Bank possesses several factors that make it suitable for successfully implementing a spatial crowdsourcing application like SRMS. Firstly, there is high accessibility to smartphones, with approximately 72% of the West Bank population aged 10 and above owning smartphones equipped with GPS sensors [79]. Secondly, there is a significant level of digital knowledge, with 51.4% of the population capable of sending photos and videos via the Internet. Thirdly, there is high accessibility to the Internet, around 91.1% of West Bank residents aged 10 and above use the Internet at least once a day, with approximately 98% accessing the Internet through smartphones. Fourthly, cellular internet access is widely available, with around 35.4% of WB residents connected to Third-generation mobile phone networks (3G), and 34% connected through Israeli cellular companies [79].

3.2. SRMS UCD

This section highlights the application of the UCD approach using personas and scenario techniques. An online survey was conducted in early 2021 to implement this approach, targeting Palestinian travelers in the West Bank. The decision to use an online survey was driven by several factors, including the physical distance of the researcher from the study area, cost-effectiveness, convenience, high accessibility, and the ability to ensure data accuracy [80].

The survey sample size was determined based on the population size, expected proportion, and desired confidence level to achieve a representative sample that can generalize the findings to the larger population. For this study, the population for this survey consists of Palestinian interurban travelers experiencing mobility restrictions while traveling for working or studying purposes in the West Bank. The population size was reported to be 592,966, which formed a proportion of 9% according to statistics obtained from the Palestinian Central Bureau of Statistics [81]. Based on these parameters, the survey sample size was calculated to be 126 to ensure a 95% confidence level. Around 185 responses were collected and preprocessed. Preprocessing involved eliminating incomplete and inconsistent responses. By removing these responses, the dataset was refined to include only valid and reliable data, 129 responses.

3.2.1. Travelers Profile

The survey sample is classified into three age groups, including (i) young adults aged 20–35, accounting for 84.4%, (ii) middle-aged adults aged 36–55, making up 8.5% of the sample, while (iii) older adults aged 56 and above comprising 6.9%. Regarding the educational level, the majority of the sample, 93%, have a university education, while 7% have finished secondary school. The professional status could be summarized as more than half are full-time, 54.2%, 6.2% are part-time, and 12.4% are unemployed. Around 26.3% of the sample consists of students. Figure 10 shows the travelers' profile information.

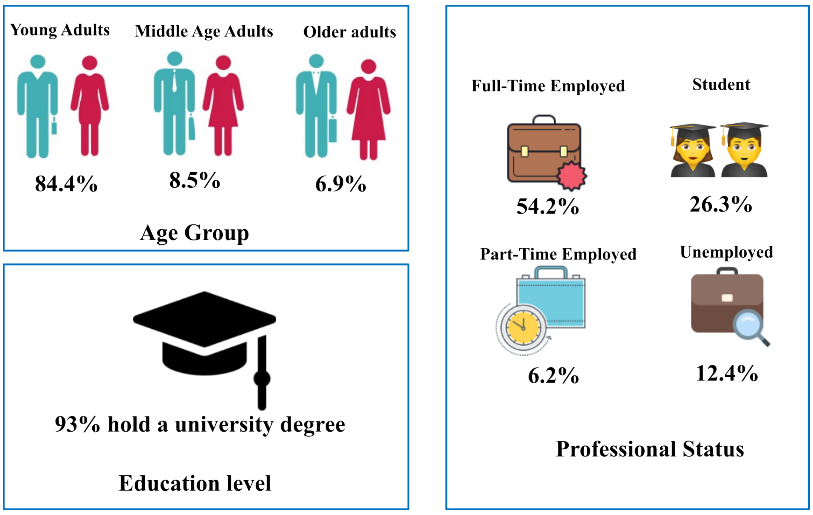

Figure 10. Participants' personal profile.

From the general profile, the sample comprises mainly active young adults, well-educated and working professionals. This means that this category has specific preferences and expectations compared with other age groups when tailoring the design and features of the SRMS platform. They are typically enthusiastic, familiar with smart technology, and comfortable with digital platforms. These characteristics refined the design and features of the proposed SRMS platform. It should include intuitive user interfaces, interactive elements, mobile compatibility, social sharing capabilities, and easy navigation and access to its features even with limited time.

3.2.2. Traveling Characteristics

Figure 11 shows the traveling characteristics, including traveling cost, time, frequency, and mode of transportation. Most of the sample, 62.9%, commute at least once per week: 39.6% traveling daily and 23.3% traveling weekly. And 14% of the sample reported traveling monthly, while 23.1% traveled less frequently than that.

Regarding traveling time during weekdays, 44% of the sample reported traveling for less than an hour. This percentage decreases to 27% during weekends. Approximately 34% of the respondents spend 1–2 hours traveling on weekdays, which increase to 42.6% during the weekend. For 12.4% of the sample, weekday traveling time exceeded three hours, while it reached 21% during weekends. Around 9.2% traveled more than three hours, with a similar percentage on weekends.

The traveling cost could be classified into four categories, including (i) majority spending range, forms 35% who are spending between 200–400 Israeli New Shekel (ILS), which could be considered moderate travel cost; (ii) higher spending range, around 24% of the sample spends more than 600 ILS, which is considered expensive commute, (iii) intermediate spending range, around 18.6% spend between 400–600 ILS; (iv) lower spending range, forms 21.6% of the sample spend less than 200 ILS. Overall, these findings indicate that the survey sample exhibits varying traveling costs.

Regarding the traveling mode, around 36.4% used public transportation only, including (bus, shared taxi, and cab taxis), while the majority used multi-modes, including private cars, carpooling, public transport, and active modes with variate percentages 44.8%, 28.7%, and, 15.1%, and 11.4% respectively. These findings indicate that the survey participants utilize diverse transportation modes, with multi-modal travel being the most common approach.

These findings indicate that most participants regularly travel either daily or weekly. Also, results show that the commuting times differ between weekdays and weekends, with longer commutes during weekends. This suggests that the platform features should provide continuous information for travelers, such as real-time information on traffic conditions and route planning, which helps optimize traveling time effectively. Additionally, when designing the SRMS platform, it's important to consider the needs of users who engage in multi-modal travel, providing features that facilitate planning and coordination across different modes.

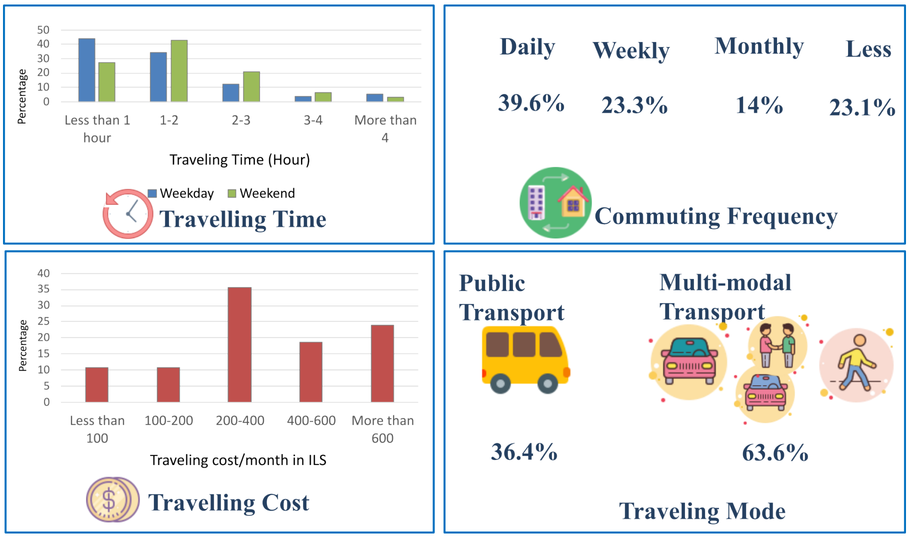

Figure 11. Participants' traveling characteristics.

3.2.3. Travelers' Interests and Willingness

This section investigates participants' interest in urban mobility issues and the proposed solutions. Some of these are related to the SRMS objectives. This will provide insight into the participants' expectations. Also, this section investigates the participants' willingness to interact with the proposed solution. The platform features were included among these solutions, such as using the mobile app for real-time information about mobility restrictions.

The survey used a significance ranking approach, ranging from 1 (less significance) to 5 (high significance). However, considering the frequency of responses and the proximity of results, the maximum-to-minimum value ratio was considered. The outcomes are depicted in Figure 12. The participants' viewpoint reveals that the most mobility concerns are efficient public transport and comfort, traveling safety, traveling time, and waiting time at transit public stations. Subsequently, there is a notable emphasis on the importance of real-time information about traffic and public transport.

Based on the ranking of significance solutions, the notable solution identified by participants is the need for a mobile app that can provide real-time information about traffic and public transport. Approximately 73% of the participants rated this solution highly significant, with ratings of 4 and 5. Regarding the participants' preparedness for these proposed solutions, more than half (59%) own smartphones, indicating a high level of technological readiness to utilize mobile apps for urban mobility purposes.

Furthermore, 62% expressed willingness to share real-time traffic information, while 59% were willing to share traveling safety information. This indicates a positive attitude towards actively participating in providing and receiving relevant information to improve the overall urban mobility experience.

Additionally, the study found that no common mobile app is used for providing real-time information. Instead, approximately 60% of participants rely on social media platforms for accessing such information.

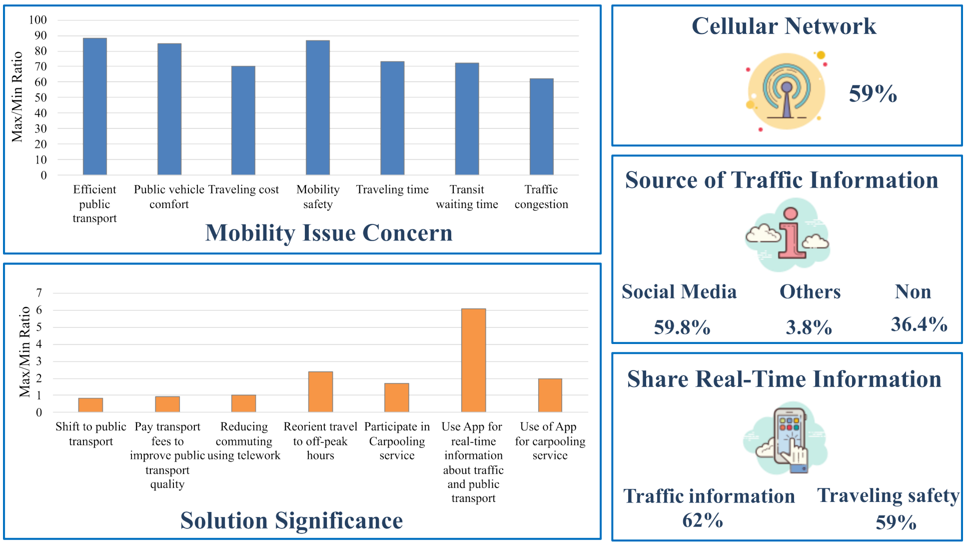

Figure 12. Significance of mobility issues and proposed solutions from participants' points of view.

3.3. SRMS Mobile Web App

The SRMS was designed using ArcGIS Experience Builder. This user-friendly web development platform allows users to create and share web applications, maps, and dashboards without extensive coding knowledge [82]. ArcGIS Experience Builder is a compatible design solution due to the following capabilities: (i) providing the principles of PWA, including flexible, responsive design framework and modern interactive interface based on widgets; (ii) providing mobile optimization with the mobile adaptive design; (iii) easily integrated with the GIS data to provide location-based services; and (iv) engaging the user in real-time through configurable widgets that can interact with data and content to optimize the end-user experience.

The design of the SRMS web mobile app was based on the results of the survey and interaction model (MoLIC) that was previously explained in the methodology. The first version of the web mobile app was created and shared with a sub-group of potential users to receive their comments and recommendations. Considering their feedback, the final version of SRMS was designed using ArcGIS Experience Builder. The architecture of SRMS UI was converted into a real-web mobile application, as illustrated in Figure 13.

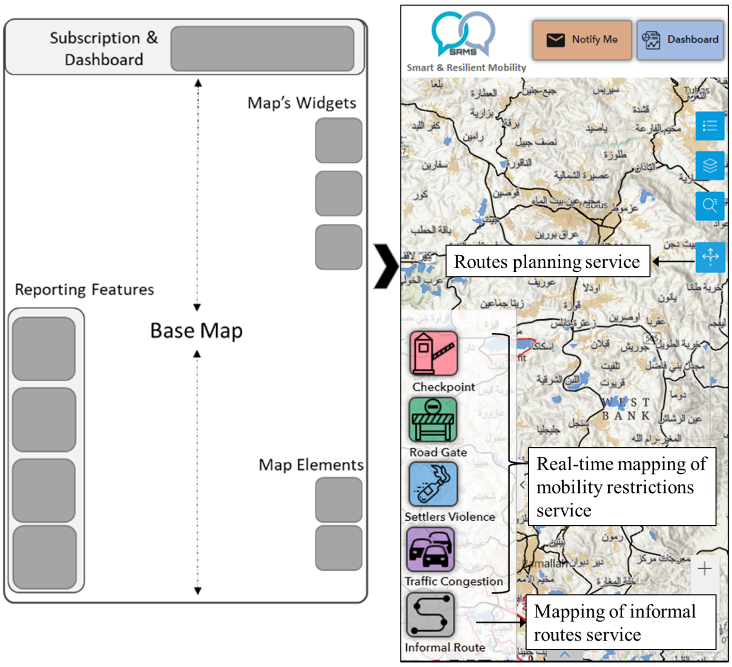

Figure 13. The final version of the SRMS UI architecture and the real application.

Figure 13 presents the SRMS basemap with various geographical elements sourced from an external spatial database. These elements include a topographic map of Wet Bank (WB), Palestinian communities, WB road networks, Israeli settlements, fixed mobility restrictions, tunnels, and the separation wall.

The sources of these elements were obtained from open and authoritative sources. Open sources such as the Israeli Information Center for Human Rights in the Occupied Territories (B'TSELEM) and the United Nations Office for the Coordination of Humanitarian Affairs (OCHA) are non-profit organizations for monitoring the violation of human rights in the WB. The authoritative sources are presented in the Ministry of Transport (MoT), Ministry of Public Work and Housing (MPWH), and the Geospatial web mapping application of the Ministry of Local Government (GeoMoLG) [83].

The basemap provides an informative environment and acts as a repository for the spatial database, with updated attributes (back to the year 2018) for each element that can assist decision-makers in planning development. Table 3 shows the data of the SRMS base map, source attributes, and formats.

Table 3. Basemap data, sources, attributes, and formats.

Geographic Element	Data Source	Attributes	Data Format
WB Road	MoT, MPWH	Name, start and end, classification (local, regional, main), length, width, governorate, technical specification (expansion, maintenance, pavement, lighting, traffic signal, painting, notes), detection date	Esri linear Shapefile: SHP
Palestinian Communities	GeoMoLG	Name, governorate, area	Esri polygon Shapefile: SHP
Israeli Settlement	GeoMoLG	Name, governorate, population, establishment year, area	Esri polygon Shapefile: SHP
Mobility Restriction	OCHA, B'Tselem	Name, type (checkpoint, flying checkpoint, road gate), governorate	Esri point Shapefile: SHP
Separation Wall	OCHA	Status, type (fence, concrete), length	Esri linear Shapefile: SHP
Tunnel	MoT	Name, description, status	Esri point Shapefile: SHP

Besides the basemap of the SRMS platform, the main components and features of the application are the following:

- Reporting Features: Widgets designated for providing the real-time mapping of mobility restrictions service. It includes reporting different types of mobility restrictions, including checkpoints, road gates, settlers' violence, and traffic congestion. It also allows reporting of informal routes. These reporting widgets are linked to the spatial crowdsourcing tool, ArcGIS Survey123, enabling the mapping of reported mobility restrictions and informal routes.

- Maps widgets: Widgets used for interacting with the map, such as a legend, basemap layers, search functionality, and a direction widget. The direction widget provides route planning services with three different categories: safest, fastest, and emergency routes.
- Subscription and dashboard buttons: Located in the upper panel, the subscription button allows users to subscribe to the Restriction Notification System (RNS). The RNS is connected to a form-centric data system that collects users' information, such as their interest restrictions and email addresses. The dashboard button leads to an informative web page displaying a summary of the reported data during the day and the temporal distribution of traffic congestion.
- Map elements: Necessary map tools for facilitating the navigation with the basemap, including zooming in and out and detecting the user's current location.

3.4. Operation of Real-time Mapping of Mobility Restriction Service

Users can access the mapping service by visiting the SRMS, where reported data is visualized with custom colors based on the event types (checkpoint: red, road gate: green, settlers' violence: blue, traffic congestion: purple), as shown in Figure 14. The map displays real-time events reported by users and remains visible for 24 hours before being removed. Users can zoom in and out of the map to view events at different scales and filter events by type using the interactive layer widget on the right side of the screen.

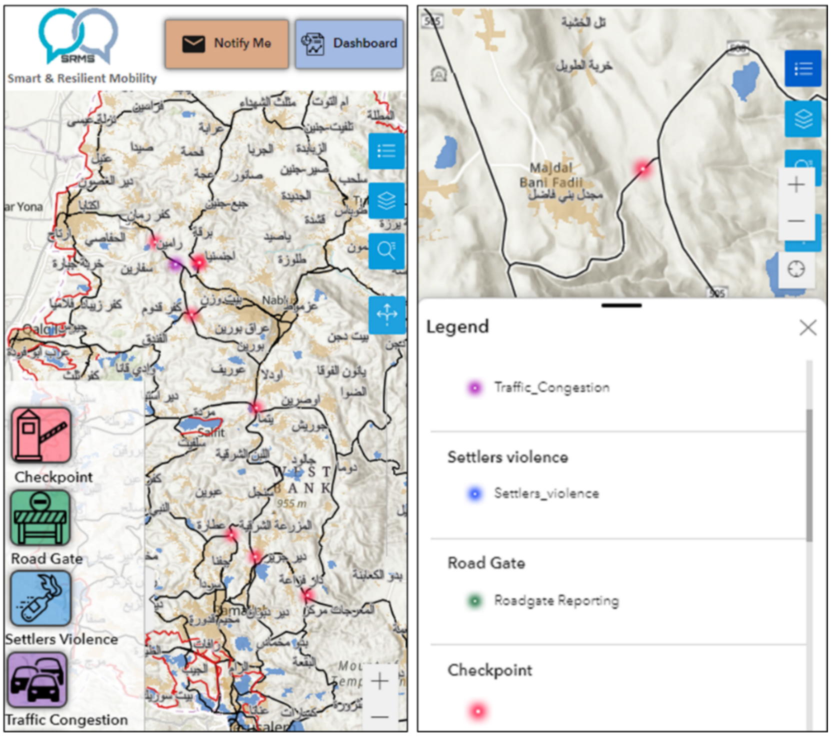

Figure 14. Reported mobility restrictions.

To report a mobility restriction, users can select one of the restriction-type icons provided in the reporting features of the SRMS platform. This action will redirect them to a reporting page developed using ArcGIS Survey123. The reporting page captures essential information about the mobility restrictions, including the restrictions' description, location, and time.

The reporting page is designed to minimize user intervention. The date and time fields are auto-filled with read-only features to ensure the accuracy of timestamp data. This reduces the chances of user error or manipulation. Additionally, with the user's permission, the location field is auto-detected based on the GPS mobile data. This feature saves users from manually inputting their location and helps ensure the accuracy of the reported event's location information. Figure 15 visualizes this reporting page and its features. Additionally, users can record a voice note to provide additional details about the reported event.

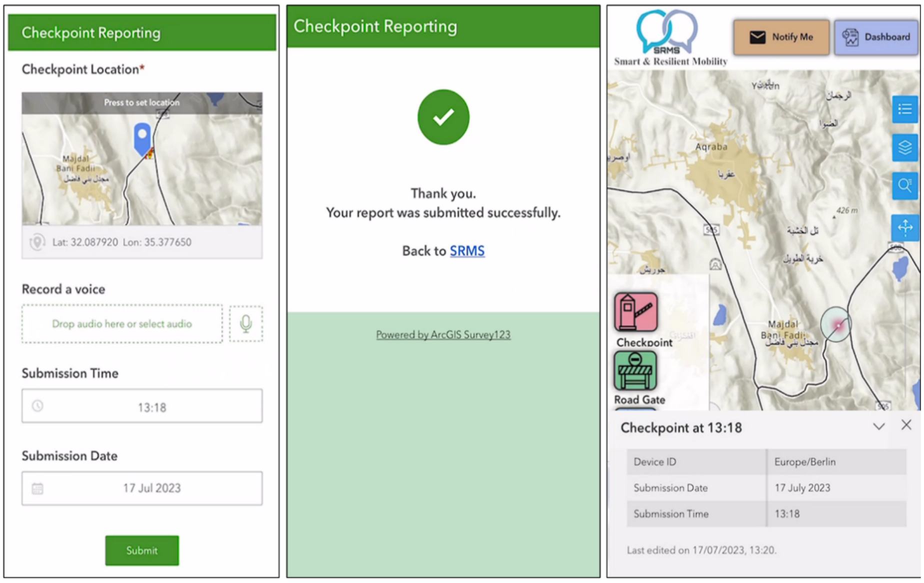

Figure 15. Reporting page, submission confirmation message, and reporting results in SRMS application.

4. Conclusion

This article addressed the pressing issue of disruptive traffic events and their significant impact on the sustainable development of communities, particularly in complex urban environments subjected to various mobility restrictions. The research has contributed to this challenge by developing a comprehensive smart platform known as the SRMS platform, specifically designed to manage mobility restrictions in the Palestinian territories. This contribution was originated by identified gaps in the existing literature regarding smart approaches and technologies for managing traffic disruptions, particularly the absence of comprehensive strategies and meaningful engagement of travelers in the management process.

The study developed the architectural framework of the SRMS platform, employing a layered system providing integrated services, including real-time mapping of mobility restrictions, a prompt notification system, informal route mapping, and alternative path suggestions. Additionally, it proposes methodologies to involve users and citizens in the solution by adopting spatial crowdsourcing as the primary source of mobility restriction data and embracing a user-centered design approach during the platform's development.

The proposed SRMS architecture was implemented in the West Bank, where mobility restrictions are a daily challenge. It assessed the feasibility of the Palestinian community adopting SRMS as an innovative solution through investigative survey studies targeting potential users. These surveys explored citizens' needs and preferences, shaping the design of the SRMS web mobile application from a human-centered design perspective. The provided services were customized accordingly using the capabilities of ArcGIS Online and ArcGIS Experience Builder.

This research faced some limitations concerning the limited dissemination of the platform among the public hindered its widespread usage and interaction. This limitation impacted the volume of data received, which, in turn, constrained further validation, and data and user quality analysis. Another limitation concerns time, which restricted the ability to investigate the long-term impacts of the SRMS platform on mobility patterns in the Palestinian territories. Future work aims to expand the study by assessing the accuracy and efficiency of the developed platform and its services across a wider user base in the West Bank. Additionally, a comprehensive examination will be conducted to highlight the data privacy and quality assurance protocols implemented in the SRMS platform. Furthermore, there is interest in integrating the Information and Communication Technology (ICT) and Decision Support System (DSS) proposed in this study with Transport System Models (TSM). These models simulate transport systems under both ordinary and extraordinary conditions, enabling the effective visualization of the future [67]. Moreover, there is potential for incorporating the concept of Mobility as a Service (MaaS) into the platform design. This could involve expanding the SRMS platform to encompass various modes of transportation, such as public transit and ridesharing. Additionally, personalized travel planning features could be implemented to cater to individual preferences, mobility needs, and real-time traffic conditions, thereby enhancing the management of traffic disruptions.

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Data Availability

Data supporting this study are openly available from HAL at https://theses.hal.science/tel-04457418.

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Conflicts of Interest

The author has no conflict of interest to declare.

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