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Article

A GIS-Based Approach to Fostering Sustainable Mobility and Combating Social Isolation for the Rural Elderly

Luís Branco [1] and Bertha Santos [1,2,3,*]

[1] Department of Civil Engineering and Architecture, University of Beira Interior, 6200-358 Covilhã, Portugal; luis.branco@ubi.pt
[2] GeoBioSciences, GeoTechnologies and GeoEngineering (GEOBIOTEC) Research Unit, Department of Civil Engineering and Architecture, University of Beira Interior, 6200-358 Covilhã, Portugal
[3] Civil Engineering Research and Innovation for Sustainability (CERIS) Research Unit, Instituto Superior Técnico, University of Lisbon, 1049-001 Lisbon, Portugal
* Correspondence: bsantos@ubi.pt

Abstract

The growing demographic trend of an aging population, particularly in remote rural areas, exacerbates social isolation and limits access to essential goods and services. This vulnerability highlights a pressing need to develop sustainable solutions for their mobility and support. Using Geographic Information Systems (GISs) and network analysis, a workflow was developed to optimize road-based transport for the elderly. The analysis utilized an electric vehicle, with its range limitations, influenced by road slopes, being a critical variable for assessing route efficiency. Two potential solutions were investigated: (1) the delivery of goods and medicines and (2) the transport of passengers and medicines. The methodology was tested using the Municipality of Seia, Portugal, as a case study, with a defined weekly visit frequency. The results demonstrate that both proposed solutions are technically viable for implementation, with the transport of passengers and medicines being the most effective option. This study provides a foundational framework for developing practical, demand-oriented, sustainable transport and logistics services to support isolated elderly populations.

Keywords: elderly population; rural areas; social isolation; Geographic Information Systems (GISs); network analysis; route optimization

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1. Introduction

The aging population is growing globally, particularly within the European Union (EU), with projections suggesting that by 2030, individuals aged 65 and over will constitute 30% of the total population [1–3]. This demographic shift is especially pronounced in remote rural areas, where it leads to isolation and limited access to essential goods and services, often due to a lack of robust public transportation [1,3–5]. In Portugal's interior, this phenomenon is deeply tied to a long-standing pattern of rural depopulation, driven by a lack of professional opportunities for young people who migrate to urban centers. In contrast, older adults tend to remain in rural areas, feeling a strong connection to their home environment, and are often joined by others who return upon retirement in search of a better quality of life. This combination of factors contributes to an increasingly older population in these regions.

The geographical isolation of many rural areas and low population density makes it difficult to establish a financially viable public transportation network [6]. Several factors compound these mobility challenges for the elderly, as many no longer renew their driving licenses, with a notable gender disparity where women, who have a longer life expectancy, are less likely to drive [6–9]. This combination of geographic and social isolation puts a significant portion of the elderly population at risk, highlighting their need for support to maintain a dignified quality of life. Research suggests that unequal access to health and food services negatively affects the health and well-being of older adults living in rural and low-density communities [4,10–12].

1.1. Literature Review

A literature review revealed a limited number of studies on the accessibility of essential health and food retail services for older adults in rural and low-density regions using GISs. Most of these studies were conducted in Europe [5,6], Japan [3,4,12], and the United States [13,14]. They primarily focused on evaluating accessibility to health [6,10,12,13,15] and food services [3,4] via public transportation. A consistent conclusion from this research is that those in rural areas face significant challenges in accessing these essential services. Furthermore, the study by Reshadat et al. [8] in Iran found that older adults had better access to health centers in urban areas compared to rural areas, and the study of Yi-Hsuan et al. [16] stated that buses are the most used mode of transportation for the elderly. These studies can also be classified as either accessibility-focused, like [3–6,10,12–14], or service distribution-focused, such as [3,4,16,17].

All studies highlight and recommend the use of geospatial analysis to help to identify deprived areas to support decision-making on the appropriate planning and organization of these services for the elderly population living in rural areas. Among the most used GIS approaches are the use of the buffer tool [16,17] and network analysis based on Dijkstra's algorithm [18] for determining the shortest and fastest routes [13], service areas [10,12], and the origin-destination cost matrix [6]. Network analysis is a critical GIS function that uses computational algorithms to determine optimal routes and service areas within a defined network of roads and intersections, helping individuals and organizations identify efficient paths and leading to significant resource savings [19,20].

However, current research has yet to explore two critical areas: the operational design of these services for low-density rural areas (specifying routes, time windows, service times, capacity constraints) and the integration of real-world electric vehicle energy/range limitations. To address these challenges, this study proposes a solution that leverages Network Analysis (NA) within Geographic Information Systems (GISs). The solution combines key functionalities such as the service area, OD cost matrix, vehicle routing problem, and route analysis.

1.2. Objective and Structure

This study, aligned with the concept of the "old" elderly (aged 75 or older) as defined by Alsnih and Hensher [9], focuses on developing a system for transporting individuals and delivering essential goods and medicines to rural elderly residents. To address this challenge, a GIS-based network analysis and contextual studies will be used to gather demographic and road network data. This methodology will be applied to examine two primary logistical solutions: (1) the weekly delivery of goods and medicines and (2) the weekly transport of passengers and medicines to and from a municipal center. The analysis will model the use of electric vehicles, factoring in how road slopes influence their range. This is performed to support environmental goals and align with the growing adoption of quiet and efficient electric fleets [21–23]. In doing so, this study fills a critical research gap by providing a methodology for creating tangible, customized public transport solutions for the rural elderly. It advances existing research, which often overlooks key factors like road slope and electric vehicle limitations and primarily evaluates the accessibility and distribution of essential services.

This manuscript is structured into four sections. Section 1, the introduction, outlines the research motivation, reviews relevant literature, and states the study's objectives. Section 2 establishes the foundational concepts and methodology, including the transport service solutions under investigation. The analysis of a case study is detailed in Section 3, along with the results achieved. Finally, Section 4 offers a discussion of the findings and conclusions.

2. Material and Methods

This section opens with preliminary considerations regarding network analysis and the performance of electric vehicles as a function of road slope. A thorough understanding of these aspects is crucial for the proper formulation of the proposed methodological framework, which is presented subsequently. The section concludes with a description of two transport services considered essential for the rural elderly, which are modeled in the case study presented.

2.1. Network Analysis

In the context of this study, a network is a set of interconnected lines, or arcs, and vertices through which movement can occur, in the sense of the graph theory [20,24]. The arcs represent the connections between points (roads), known as nodes or vertices (crossings), with each connection having a start and an end point. The direction in which an arc is digitized often defines the direction of movement within the network. This movement can be either directed (one-way, where a line points from one vertex to another) or undirected (two-way, where there is no directional distinction between connected vertices) [25]. A road network can include both directed elements (one-way streets) and undirected elements (two-way streets). Each part of the network can have unique characteristics, like speed limits and travel times, which influence its function (cost). By setting parameters for these network elements and their connectivity, we can calculate routes between points.

The most fundamental problem is finding the shortest or fastest route, which is a crucial algorithm in network analysis (Dijkstra's algorithm) [18,25,26]. More complex analyses can also be performed, including: Closest Facility, which identifies the nearest facility to a specific location and determines the most efficient route to it; Service Area, which calculates the coverage area, in terms of distance or travel time, that is accessible from or to one or more locations; Location-Allocation, which identifies the best location from multiple options, taking into account specific demand points; Origin-Destination Cost Matrix, which calculates the cost (e.g., travel time or distance) from each origin point to every destination point; and the Vehicle Routing Problem (VRP), which, given a fleet of vehicles, aims to determine the most efficient routes for each vehicle to ensure the required coverage [27].

Network analysis for vehicle movement is a fundamental field within GISs, commonly included in the domain of GIS applied to transportation (GIS-T). This field has become increasingly prominent and is considered one of the most significant GIS applications. Several authors highlight the benefits of interdisciplinary research in this area [28], suggesting that GIS techniques must be flexible enough to allow for parameterization based on the expertise of specialists in various fields. In transportation, relevant parameters can include speed, vehicle range, the impact of slopes, the need to avoid certain areas (e.g., crime hotspots), and prioritizing specific routes. Therefore, it is essential for any solution to be flexible enough to allow for future parameter adjustments. One parameter with a significant impact is speed. Network analysis studies have used a range of speeds depending on the vehicle type, road hierarchy class, or road environment. For example, Tome et al. [29] adopted speeds between 30 km/h and 70 km/h for private vehicles and 20 km/h for public transport in urban environments, and Domingos [30] considered speeds ranging from 30 km/h to 50 km/h in urban areas and 120 km/h for highways.

2.2. Slopes and Electric Vehicles

A key concern when designing a solution with electric vehicles is their range, as it is crucial to ensure a vehicle can complete a full day's route without needing to recharge. This limited range is a primary disadvantage of electric vehicles. A vehicle's range is influenced by several factors, including temperature, weight, driving style, distance traveled, and road slope [31,32]. The slope is of particular interest because, unlike environmental or behavioral factors, it is a constant physical property of the route. In areas with steep hills and varied terrain, slope becomes an even more critical variable. For this study, it was considered necessary to apply a function to the road network that calculates range loss based on slope-specific weighting factors.

Despite its clear influence, most existing studies do not consider or provide a general function explicitly linking vehicle electricity consumption or range to slope. While some models explore how road slope influences driving behavior [33,34], and Zhu [35] further investigated vehicle energy consumption using one of these models, there has been no specific study on the effects of road slope on the electricity consumption of electric vehicles [36]. However, a study by Yang et al. [36] provides useful data from tests conducted on 11 vehicles under various conditions of acceleration, braking, and constant speed. The numerical results show that electric vehicle's electricity consumption increases with the uphill's tilt angle and decreases with the downhill's tilt angle. These results are used to estimate weighting factors for range loss based on slope. For uphill, the findings revealed a notable increase in consumption: approximately 28% from a 1° to a 2° slope, 22% from a 2° to a 3° slope, and a 56% increase from a 1° to a 3° slope. This increase in consumption directly corresponds to a reduction in range. Table 1 presents the specific values from the research.

Table 1. Consumption as a function of slope [36].

Slope	**Uphill**			**Downhill**		
	1°	**2°**	**3°**	**1°**	**2°**	**3°**
Electric consumption (10^6 J)	5.4988	7.0385	8.5913	2.4726	1.8938	1.3576

Note: 1° is approximately 1.75 %.

2.3. Methodological Approach

The project workflow begins with a demographic analysis to understand the project's necessity and to gather data for system calibration. This initial phase involves analyzing the population density of elderly residents and their distribution across the region, along with other available official statistical data (census).

Next, a comprehensive analysis of the road network is conducted to identify any vulnerabilities that will help define the project's design. In this intermediate phase, the network is prepared with all necessary corrections, constraints, and criteria.

Following this preparation, a global analysis of distances and travel times is carried out using network analysis methods. In the final phase, the most suitable method for route determination is selected and applied to produce the results, with any necessary corrections made as needed.

The overall workflow is presented in Figure 1.

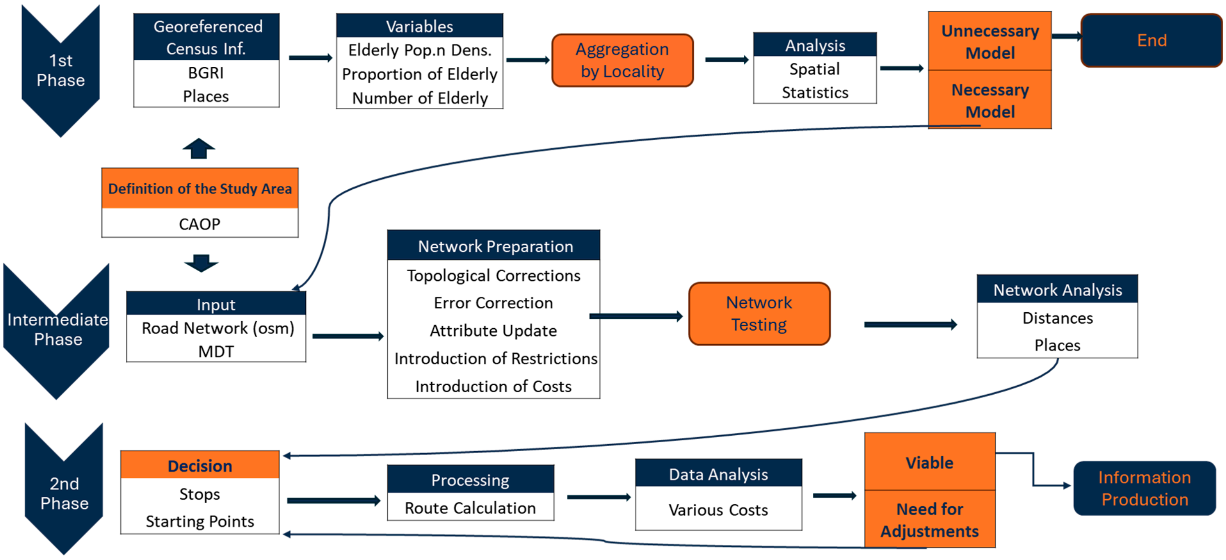


Figure 1. Overall workflow for defining elderly transport services. Note: BGRI is the Portuguese Geographic Information Reference Base, and CAOP is the Official Administrative Map of Portugal.

2.4. Transport Service Solutions

This study explores two potential solutions to address the isolation of the elderly in rural and low-density regions. The first is a delivery service for essential goods and medicines. The second is a hybrid model that combines medicine delivery with a transportation service, bringing residents to urban centers that offer key healthcare and other services.

The delivery service solution focuses on providing essential goods and medicines to elderly residents on a weekly basis. The goal is to establish a daily route that includes stops at a pharmacy for medicines and a supermarket for groceries, which are then delivered to various rural localities. To make the routes efficient, residents would preorder items through their Parish Councils (PCs) via phone, in-person, or other designated methods. To optimize delivery, a specific drop-off point, such as the PC itself, would be established. The municipality would need to define these points and create alternatives for those unable to reach them. To use the service, residents would be required to register in advance and pay a small fee based on their financial situation.

The hybrid transport and delivery service also include medicine delivery but adds a transportation component. The service would transport residents from their localities to the municipal center in the morning and back in the afternoon, once a week. Those who are unwilling or unable to travel would still have their medicines delivered. For logistical efficiency, the same vehicle would be used for both transporting people and delivering medicines. Stops for people and medicines would be combined whenever possible to optimize the route. In some localities, a separate stop might be designated exclusively for passengers, while another serves both people and delivers medicines. Unlike the first solution, this approach excludes grocery delivery since people would have the opportunity to shop for themselves. Passengers would be dropped off at a central urban transport stop to minimize walking distances.

Both proposed approaches rely on agreements between the municipality, pharmacies, and supermarkets. Financial transactions would be handled by the municipality, which could potentially receive a discount from retailers to help offset the service costs. A more in-depth study would be required to define the administrative procedures and logistical details of the final design, as the current study's focus is on the transportation component.

More specific aspects that may arise during the analysis and definition of the proposed transport service solutions are exemplified in the following section, Case study.

3. Case Study

3.1. Study Area

The study area is the municipality of Seia, located in the Guarda District of Portugal. According to the 2021 Census, the district has 14,3019 inhabitants, with 21,755 residing in Seia. The municipality has a population density of 49.9 inhabitants per km^2.

This territory is characterized by diverse geographical features, including mountains, valleys, plateaus, and rivers. Although Seia covers a total area of 43,569.83 hectares, only 2924.47 hectares correspond to statistical places. These are defined as population clusters with 10 or more housing units used for residential purposes and that have their own name. The data for these localities, which is used in this study, was obtained from the website of the Instituto Nacional de Estatística (INE) (Statistics Portugal) [37] and is based on the 2021 Census. The information is summarized in Table 2.

Table 2. Summary of demographic and geographic statistics for Seia.

Total Area (ha)	43,568.83
Area of statistical places (ha)	2924.47
Total population (inhabitants)	21,755
Elderly population (inhabitants)	3832
Proportion of elderly (%)	17.61
Elderly men (inhabitants)	1530
Elderly women (inhabitants)	2302
Proportion of elderly women (%)	60.07

The population densities of elderly residents were calculated using the area of statistical places, which excludes the municipality's extensive uninhabited regions. This approach provides valuable geographical insights, allowing for the identification of parishes with the highest density of elderly residents and the distribution of the elderly population relative to the total population.

Interestingly, there is a higher concentration of elderly residents in areas that are farther from the municipal center of Seia, as shown on the left side of Figure 2. The population density of elderly individuals per hectare of inhabited areas in each parish is shown on the right side of the same figure.

The results suggest that implementing the proposed transport services would be beneficial for the municipality of Seia. Based on data from the 2021 Census, the municipality has 3832 elderly residents. Approximately 2022 of these individuals live in Seia or in nearby areas that already have regular transportation. Therefore, the remaining 1810 individuals are the ones who would most likely benefit from the transport solutions proposed in this study.

3.2. Network Preparation

To ensure the accuracy of the Seia road network for this study, specific adjustments were made to the data, which was sourced from OpenStreetMap [38]. The initial flow direction was determined by both the digitization of the arcs and an attribute field for one-way ('F') or two-way ('B') traffic. Roundabouts were also adjusted to ensure correct circulation. The network's data also included an 'fclass' attribute field for road class, though some required manual correction. The 'maxspeed' attribute field was then used to define the average speed for each arc, as shown in the code presented in Figure 3.

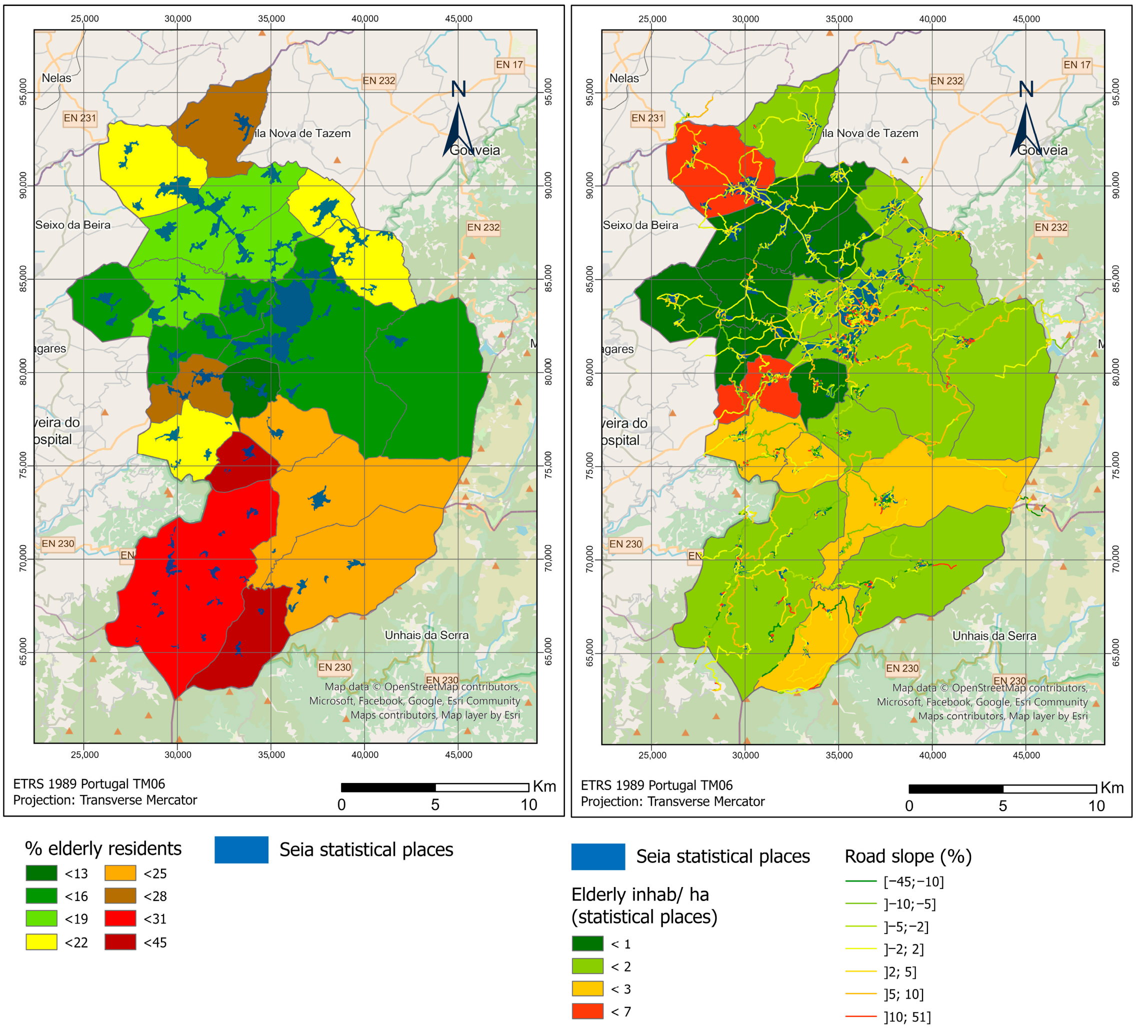


Figure 2. Proportion of elderly residents (**left**), population density of elderly residents (**right**) and road network slope (**right**) in the study area.

```
set_max_speed(!fclass!)
def set_max_speed(fclass):
    if fclass in ('primary', 'primary_link'):
        return 60
    elif fclass in ('secondary', 'secondary_link'):
        return 40
    elif fclass in ('tertiary', 'tertiary_link'):
        return 25
    elif fclass in ('living_street', 'residential', 'service', 'unclassified'):
        return 20
    else:
        return 0
set max speed(fclass)
```

Figure 3. Speed definition code.

Speeds were initially assigned based on previous studies [28,29]. To further calibrate these values, a trip was conducted using Seia's public transport service named "VAIeVEM", which operates a vehicle similar to the one proposed for this study. This trip, which covered 45 stops in the urban area, helped to verify average stop times and adjust the speeds for analysis. Speeds were recorded at 150 points (excluding stops), with an observed average of 27 km/h. Final adjustments were then made based on local knowledge of the area.

To estimate the loss of vehicle range due to slope, a Digital Elevation Model (DEM) with a spatial resolution of 30 m/px was used. The DEM, retrieved from the Copernicus

Data Space Ecosystem [39], allowed for the calculation of the slope for each arc in the road network (see Figure 2). The slope, expressed as a percentage, was calculated using Equation (1). This equation compares the altitude difference between the start and end vertices of each arc with its length. A positive slope indicates an uphill direction (from a lower to a higher altitude), while a negative slope indicates a downhill direction (from a higher to a lower altitude).

$$d = \frac{end_h - start_h}{Shape_{Leng}} \times 100 \tag{1}$$

3.3. Vehicle Capacity and Service Demand

The proposed vehicle is a passenger minibus with up to 22 seats. An example is the Iveco eDaily Minibus, which has a range of up to 200 km and can be specially configured, including adaptations for people with mobility impairments. The potential number of users per route was estimated based on demographic data, driving license holders and the number of routes. Considering the total elderly population in Portugal (1,179,613) and the number of elderly drivers (370,747), approximately 31% hold a driving license [7,37]. Accounting for couples, where at least one partner may have a license, the proportion increases to around 50%.

Accurately predicting service usage among rural elderly residents requires a context-specific study to calibrate the participation rate based on local demographic conditions, travel habits, and service availability. For the purpose of modeling and demonstrating the approach's feasibility, a conservative 15% participation rate was assumed for the baseline scenario. This value was chosen because it not only represents a plausible estimate but also approximates the maximum passenger capacity of the proposed electric vehicle. However, it is acknowledged that other rates and/or contexts may require a larger vehicle fleet or an increase in vehicle seating capacity.

Assuming a 15% participation rate and 5 routes in a week, one per workday (two were subdivided totaling 7 routes): $(1810 \times 0.5 \times 0.15)/7 = 20$ people per route. Even so, the routes must allow some flexibility to potentially return to certain places in case capacity is exceeded.

3.4. Restrictions and Costs

Several restrictions were applied to the road network to ensure realistic route calculations. The first restriction involved one-way streets: arcs designated as 'F' were considered one-way, with their traffic flow coinciding with their digitization direction. Reverse circulation on these arcs was therefore prohibited. The second restriction relates to slope: arcs with a slope exceeding 10% were set to be "avoided." This was operationalized by multiplying the travel cost of these arcs by a factor of 5. Two symmetrical functions were applied, depending on the digitization direction, to account for uphill road segments.

Relating costs, general travel costs included the distance (in km), which was automatically calculated, and travel time (in minutes), which was determined by the assigned speed for each arc.

The analysis also included vehicle range loss (in km) for each route, incorporating slope as a key parameter with the cost factors presented in Table 3. According to a study by Yang et al. [36], energy consumption can increase by 20% to 30% for each degree of road slope, which is equivalent to a 1.75% road incline. Based on this value, a conservative approach was adopted for the model. No function was applied to reduce autonomy loss on downhill segments (Cost factor = 1.0), and less steep slopes were not heavily penalized to account for uncertainties (Cost factor = 1.2). However, for steeper slopes, stronger, yet still conservative penalties, were applied (Cost factor = 1.5 and Cost factor = 2.0), given that the available energy consumption values only go up to 3°, as reflected in Table 1.

Table 3. Proposed cost factors for autonomy (km).

Slope (%)	Cost Factor
≤2	1.0
≤5	1.2
≤10	1.5
>10	2.0

3.5. Analysis and Results

3.5.1. General Network Analysis

A "Service Area" analysis was performed to evaluate accessibility to Seia's urban center. For the analysis, travel time was used as the primary metric of geographical access. This approach provides a more accurate representation of accessibility than distance alone and aligns with the methodology of several studies on elderly transport accessibility in rural areas, such as those conducted by Reshadat et al. [10], Stentzeel et al. [6] and Fujiwara et al. [12].

As shown in Figure 4 (left), the analysis used line cut-offs at 20, 40, and 60 min of travel time from Seia Municipal Council. Polygons with cut-offs at 20, 30, and 60 min were also created to highlight areas without road access and to visually represent the municipality's division (statistical place polygons are shown in blue). The southern region is the most distant in terms of travel time, while the northern part of the municipality is largely within a 20 min travel time of Seia.

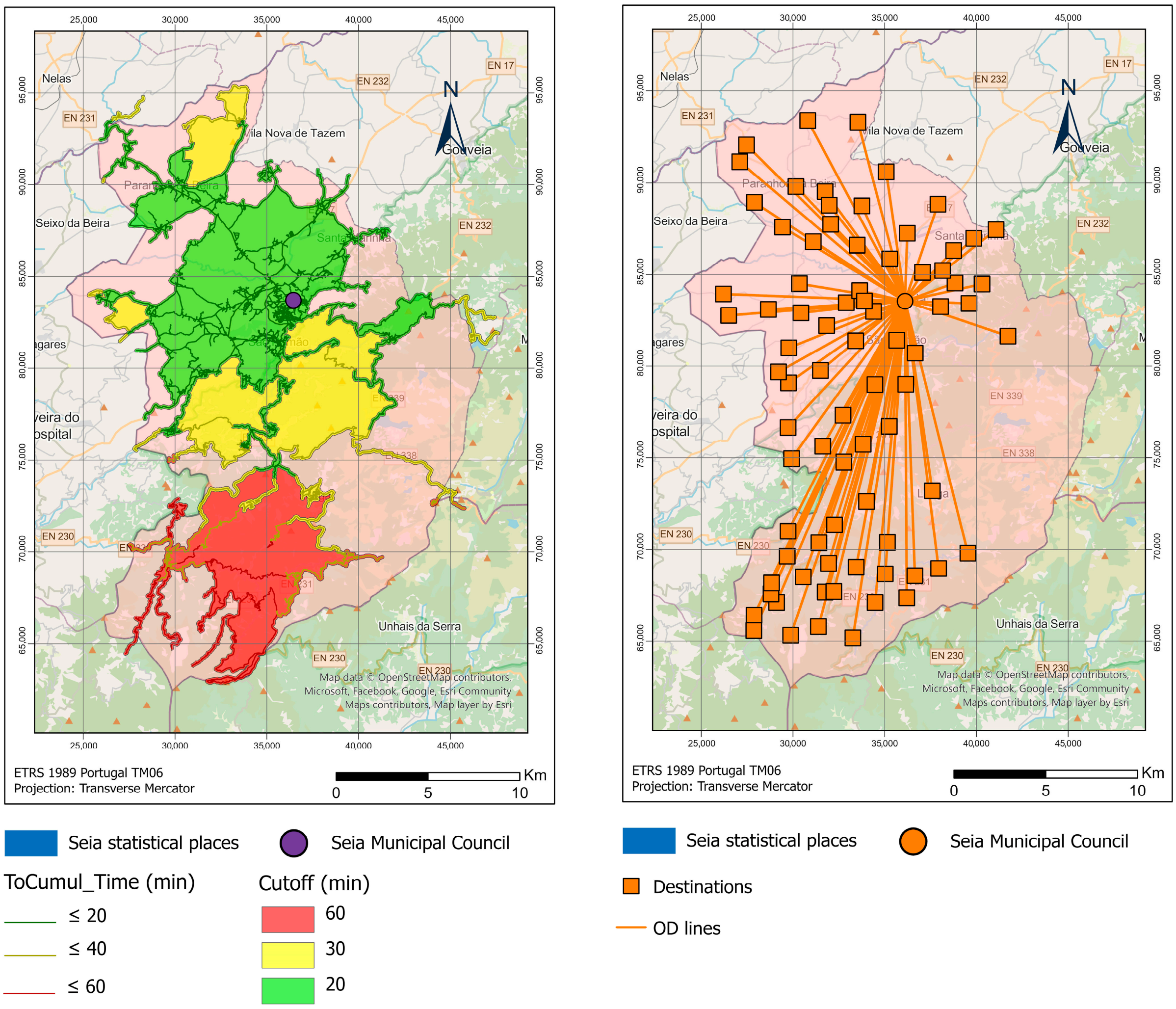


Figure 4. Service area (**left**) and origin-destination (OD) cost matrix (**right**) analysis.

Furthermore, the areas furthest from Seia are also distant from neighboring municipalities and consist of small, isolated clusters. This observation supports the use of a comfortable and reasonably fast vehicle for the second solution analyzed in this study.

An Origin-Destination (OD) Cost Matrix analysis was also conducted to further understand travel times. Seia's Municipal Council served as the origin, with the centroids of the statistical places as destinations. The farthest locality is Teixeira de Cima, at 45 km, while the place with the longest travel time is Gondufo, which is 54 min away despite being only 35 km from Seia Municipal Council. Most of the locations with the longest travel times are in the south of the municipality (>35 min). On average, the localities are 16.6 km away, with an average travel time of 21 min and 15 s. The map for this analysis is shown in Figure 4 (right).

3.5.2. Route Determination

The routes for distributing goods and medicines were determined using the workflow shown in Figure 5.

Figure 5. Workflow for determining goods and medicines distribution routes.

Five distinct routes were created, one for each day of the workweek. Each route includes fixed, daily stops at a pharmacy and a supermarket. Distribution points were selected within each locality, typically near the Parish Council or another convenient location. The following stop times were set for the model: 5 min for the pharmacy, 10 min for the supermarket, and between 8 and 10 min for the distribution points.

To define the routes, the Vehicle Routing Problem (VRP) method was applied. The model was adjusted to simulate five vehicles, one for each day. To ensure the first stop of the day was the pharmacy and the second was the supermarket, time windows were imposed, both starting at 8:00 a.m.: 10 min and 25 min, respectively. The resulting routes are shown in Figure 6. Since the VRP model could not account for range loss due to slope, the five determined routes were later analyzed individually. The graph in Figure 7 summarizes the values obtained for each route. The maximum range loss occurs on Route 4, amounting to 107 km. This is an evident increase from its length of 91 km, with an additional 16 km of range loss attributed to slope effects. Route 4 is also the longest in duration (227 min), with an expected return to the Municipal Council at 11:46 a.m.

In the passenger transport and medication distribution solution, a primary consideration, beyond vehicle capacity, was ensuring a reasonable travel time, including the return trip. The routes were divided into five sets of points, one for each day, in a configuration similar to the previous solution (goods and medicines distribution). The workflow for determining the routes is shown in Figure 8.

Each route is scheduled to begin at 7:30 a.m., with the return trip starting at 4:30 p.m. Stop times were set at 5 min for the pharmacy and Parish Councils, and 2 min for all other stops. The results are presented in Figure 9.

Due to its length, high number of stops (16 in total) and consequently the higher potential number of passengers, Route 5 was split. Route 3 (14 stops) was also divided, as its configuration allows for an intermediate passage through the bus station. For these routes, a portion of the service includes an intermediate return to the bus station in the morning and another in the afternoon to ensure all planned localities are served. Some stop sequences also required manual correction to allow for a sufficient margin in case of overcapacity and to adjust travel times. For example, Route 2 (14 stops) was modified to ensure that the passenger from the most distant local boards first. Therefore, despite its length, there was no need to split this route.

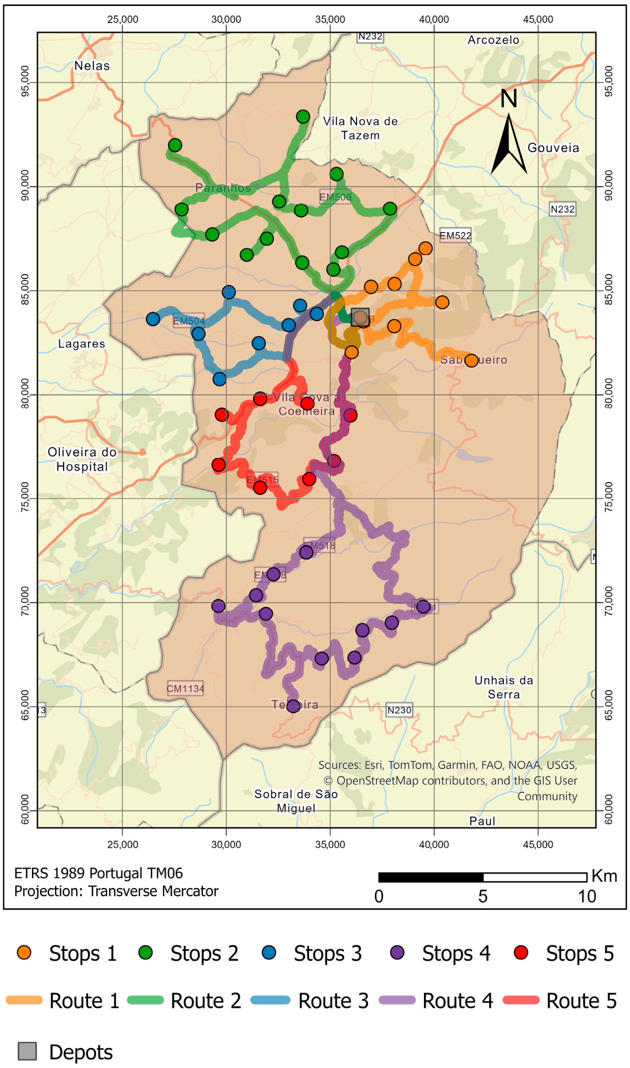


Figure 6. Goods and medicines route map.

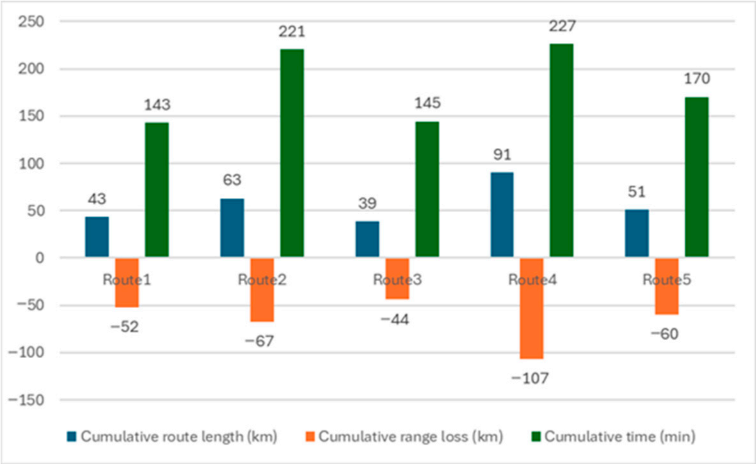


Figure 7. Key performance indicators (cumulative length, vehicle range loss, and travel time) for round-trip goods and medicines distribution routes.

Figure 8. Workflow for determining passenger transport and medication distribution routes.

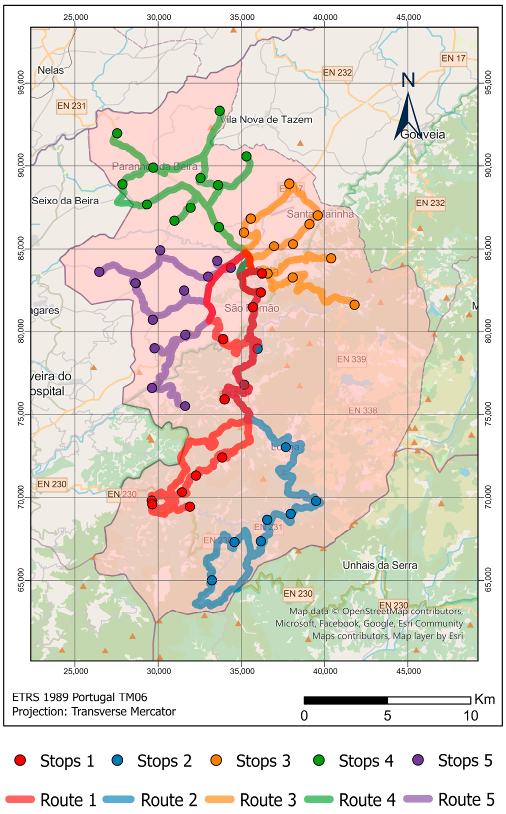


Figure 9. Passenger transport and medication distribution route map.

The graph in Figure 10 summarizes the distance, range loss and travel time (cumulative, driving and stopped) for each route. The red line indicates the vehicle's 200 km range limit. Based on this, Route 2 will require an intermediate recharge, which can be performed after the last passenger disembarks in the morning. The maximum range loss was observed on this route, which has a length of 194 km. Due to slope effects, the required range to complete the route increases to 231 km, representing a loss of 37 km of autonomy. This corresponds to an approximately 20% reduction in the vehicle's effective range.

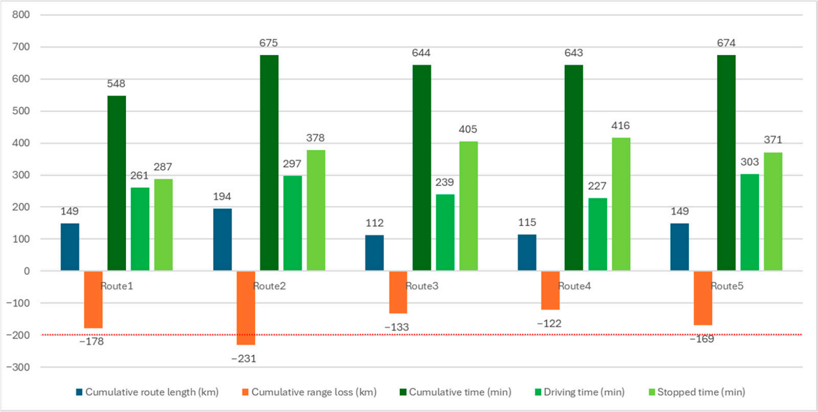
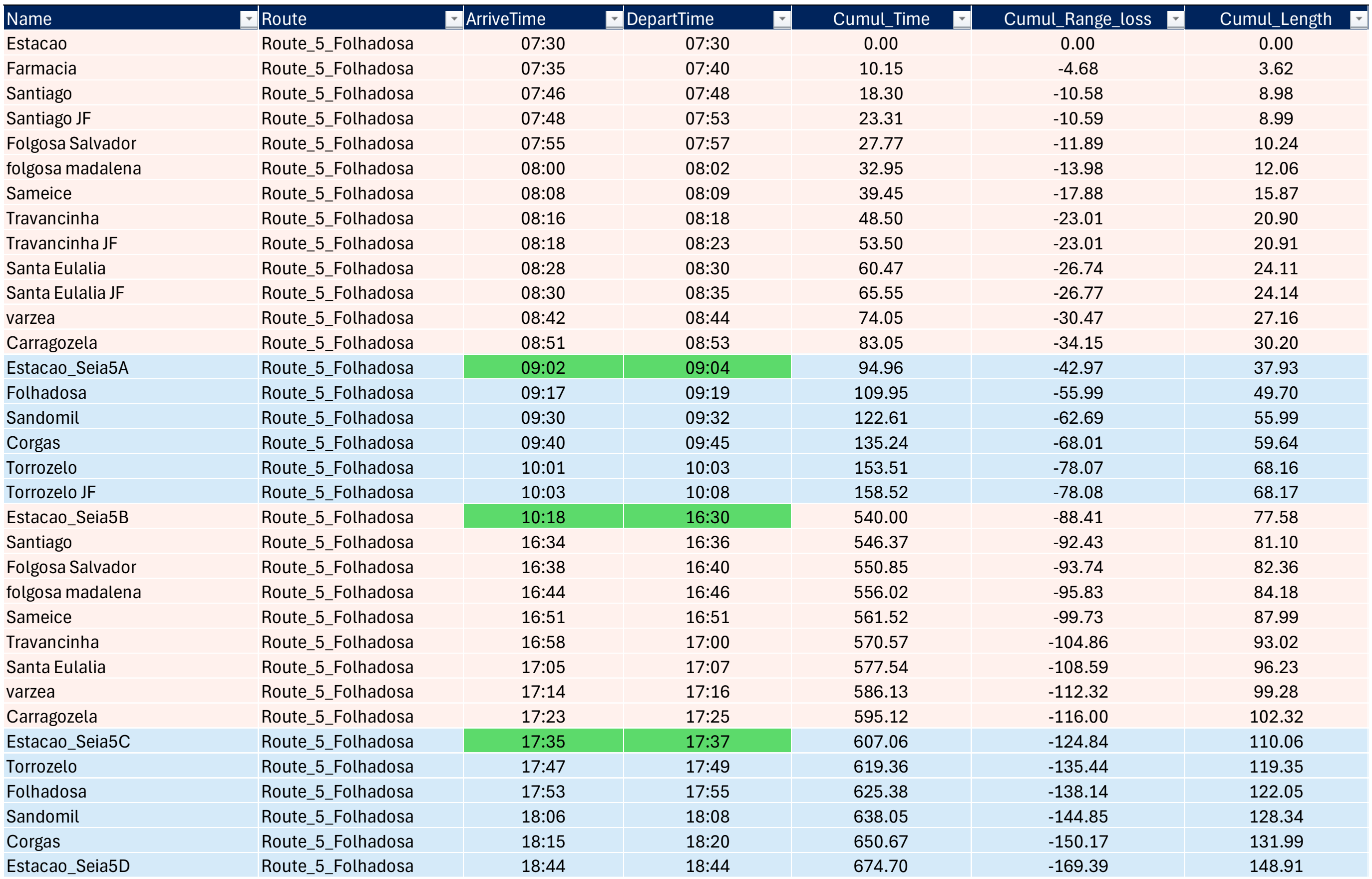


Figure 10. Key performance indicators (cumulative length, vehicle range loss, and travel time) for round-trip passenger transport and medication distribution routes.

Figure 11 presents a sample of data obtained from GIS software (ArcGIS Pro 3.5.1), filtered specifically for Route 5. As a route requiring subdivision, this case serves as a representative example. In the morning, the vehicle departs the station at 7:30 a.m. before collecting medicines. The first passenger boards at 7:46 a.m., and the first group of passengers disembarks at 9:02 a.m. A second trip then begins with the first passenger boarding at 9:17 a.m., with all remaining passengers disembarking at 10:18 a.m.



Name	Route	ArriveTime	DepartTime	Cumul_Time	Cumul_Range_loss	Cumul_Length
Estacao	Route_5_Folhadosa	07:30	07:30	0.00	0.00	0.00
Farmacia	Route_5_Folhadosa	07:35	07:40	10.15	-4.68	3.62
Santiago	Route_5_Folhadosa	07:46	07:48	18.30	-10.58	8.98
Santiago JF	Route_5_Folhadosa	07:48	07:53	23.31	-10.59	8.99
Folgosa Salvador	Route_5_Folhadosa	07:55	07:57	27.77	-11.89	10.24
folgosa madalena	Route_5_Folhadosa	08:00	08:02	32.95	-13.98	12.06
Sameice	Route_5_Folhadosa	08:08	08:09	39.45	-17.88	15.87
Travancinha	Route_5_Folhadosa	08:16	08:18	48.50	-23.01	20.90
Travancinha JF	Route_5_Folhadosa	08:18	08:23	53.50	-23.01	20.91
Santa Eulalia	Route_5_Folhadosa	08:28	08:30	60.47	-26.74	24.11
Santa Eulalia JF	Route_5_Folhadosa	08:30	08:35	65.55	-26.77	24.14
varzea	Route_5_Folhadosa	08:42	08:44	74.05	-30.47	27.16
Carragozela	Route_5_Folhadosa	08:51	08:53	83.05	-34.15	30.20
Estacao_Seia5A	Route_5_Folhadosa	09:02	09:04	94.96	-42.97	37.93
Folhadosa	Route_5_Folhadosa	09:17	09:19	109.95	-55.99	49.70
Sandomil	Route_5_Folhadosa	09:30	09:32	122.61	-62.69	55.99
Corgas	Route_5_Folhadosa	09:40	09:45	135.24	-68.01	59.64
Torrozelo	Route_5_Folhadosa	10:01	10:03	153.51	-78.07	68.16
Torrozelo JF	Route_5_Folhadosa	10:03	10:08	158.52	-78.08	68.17
Estacao_Seia5B	Route_5_Folhadosa	10:18	16:30	540.00	-88.41	77.58
Santiago	Route_5_Folhadosa	16:34	16:36	546.37	-92.43	81.10
Folgosa Salvador	Route_5_Folhadosa	16:38	16:40	550.85	-93.74	82.36
folgosa madalena	Route_5_Folhadosa	16:44	16:46	556.02	-95.83	84.18
Sameice	Route_5_Folhadosa	16:51	16:51	561.52	-99.73	87.99
Travancinha	Route_5_Folhadosa	16:58	17:00	570.57	-104.86	93.02
Santa Eulalia	Route_5_Folhadosa	17:05	17:07	577.54	-108.59	96.23
varzea	Route_5_Folhadosa	17:14	17:16	586.13	-112.32	99.28
Carragozela	Route_5_Folhadosa	17:23	17:25	595.12	-116.00	102.32
Estacao_Seia5C	Route_5_Folhadosa	17:35	17:37	607.06	-124.84	110.06
Torrozelo	Route_5_Folhadosa	17:47	17:49	619.36	-135.44	119.35
Folhadosa	Route_5_Folhadosa	17:53	17:55	625.38	-138.14	122.05
Sandomil	Route_5_Folhadosa	18:06	18:08	638.05	-144.85	128.34
Corgas	Route_5_Folhadosa	18:15	18:20	650.67	-150.17	131.99
Estacao_Seia5D	Route_5_Folhadosa	18:44	18:44	674.70	-169.39	148.91

Figure 11. Itinerary information of Route_5: arrival and departure times, cumulative distance, time, and vehicle range loss for each stop along the route. Note: The arrival and departure times for the two resulting routes from the split of Route 5 are highlighted in green.

The afternoon portion of the journey begins with the first group of passengers boarding at 4:30 p.m., followed by a second group at 5:35 p.m. The final passenger arrives at their locality at 6:15 p.m., resulting in a 35 min return trip. The data indicates a total range loss of approximately 170 km, which leaves a remaining margin of about 30 km if the vehicle cannot be recharged during the day.

4. Discussion and Conclusions

Mobility is essential and particularly important for the quality of life of the elderly population living in rural, low-density areas. It promotes transportation independence, which is crucial for this age group (over 75 years old). Traditional, fixed-route public transportation is often ill-suited for these regions, making it necessary to challenge historical assumptions and explore opportunities for more flexible transport services and technologies. This study intends to present a framework for defining transport services for passengers and goods, with a focus on the rural elderly population. The proposed approach is based on GIS network analysis to effectively address this challenge of mobility.

To test and validate the proposed approach, a case study was conducted in the municipality of Seia, Portugal. The initial demographic analysis confirmed the project's relevance by identifying significant social vulnerabilities related to an aging and isolated population within the municipality. The subsequent use of GIS spatial analysis techniques, combining route, service area, origin-destination cost matrix and vehicle routing problem analysis, provided a more detailed understanding of the local road network and accessibility, indicating that some remote localities would need to be excluded from the routes due to their remoteness and low population, which would not justify the required detours. The final phase demonstrated the project's overall feasibility. However, some details require further study to reflect the number of potential service users more accurately. The service area and origin-destination matrix analyses confirmed that weekly visits to all localities would not be feasible, particularly for the passenger transport and medication distribution service in the southern part of the municipality, a finding that is supported by the generated timetables. To address this issue, an additional vehicle or a combined solution would be necessary, such as replacing the passenger transport and medication distribution route with a goods and medicines route on a specific day of the week. Reaching this population could also be achieved by complementing the service with an on-demand customized transportation service, ensuring no community is excluded from essential transport options. This would require crucial collaboration from local municipalities, for example, by coordinating parish-level support or providing resources to extend coverage.

The findings indicate that implementing a goods and medicines delivery service is less complex than establishing a service for passenger transport and medication distribution. The latter may operate at the limit of acceptable travel time for a comfortable journey, which is difficult to determine as it depends on individual perception and context, especially for more remote localities. Residents living farther from the municipal center are frequently accustomed to longer journeys and may tolerate extended travel times more easily. In contrast, those in closer proximity may find even moderate durations inconvenient. This highlights the need to calibrate comfort thresholds to local conditions, ideally through surveys or participatory methods that capture the expectations and habits of elderly residents in distinct parts of the municipality. The slope factor also presents a challenge. While the method used to calculate range loss appears effective, a higher spatial resolution for the Digital Elevation Model (DEM) would be preferable. Nevertheless, this approach provides a better approximation than not including slope at all. The network analysis methods proved effective, allowing for the export of a comprehensive dataset in a clear table format, which facilitates the reading of timetables and costs. This data requires minimal additional processing before being made available to interested parties.

Regarding the degree of digital integration, the GIS-based planning framework could be enhanced by digital tools like booking apps or call-in systems. These tools would help aggregate demand and optimize routes. While inclusive non-digital options must remain available, it is reasonable to expect electronic ordering to become increasingly common as digital literacy rises among the elderly population.

In addition, the service must be continuously monitored and adjusted to remain responsive to changing conditions. This responsibility can be shared among various stakeholders, including private entities that benefit financially and public institutions such as municipalities, local councils, and associations. However, rural municipalities face limited resources that can hinder the adoption of new transport services solutions, such as the one proposed in this study. This can be addressed through a multifaceted strategy involving co-financing partnerships with various local entities and leveraging vehicles for corporate sponsorship through advertising. Furthermore, public funding from European and national programs can finance pilot projects and charging infrastructure, thereby reducing upfront municipal costs and helping to achieve 2050 carbon-neutrality targets. Finally, incentives for local renewable energy (such as solar) can power the electric fleet, which lowers operational costs and directly tackles the primary challenge of vehicle autonomy.

In conclusion, this approach advances existing research, which primarily evaluates the accessibility and distribution of essential services. It fills a critical gap by providing a methodology for defining tangible public transport solutions, specifically for elderly residents in rural areas who have limited access to essential services such as healthcare and food. By accounting for the specific characteristics of the territory, population, road network and the geographical distribution of services, the solutions are customized to address local inequalities (urban versus rural). These solutions are cost-efficient and demand-oriented, effectively compensating for the absence of a permanent, high-cost service. Furthermore, the model can be broadly implemented in other regions, serving as a valuable tool for local authorities to optimize transport services for the elderly, provided that the opportunities for improvement identified in this study are addressed.

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Data Availability Statement: The data used in this study are publicly and freely available on official websites. These include national statistical data, road network information, and DEM. For the case study presented, data for the city of Seia were obtained from https://www.ine.pt, https://download.geofabrik.de/ and https://dataspace.copernicus.eu/explore-data/data-collections/copernicus-contributing-missions/collections-description/COP-DEM (all accessed on 26 April 2024). The results derived from this data, for the case study, are available from the authors upon request.

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References

1. Augère-Granier, M.-L.; McEldowney, J. *Older People in the European Union's Rural Areas*; European Union: Brussels, Belgium, 2020. [CrossRef]
2. Corselli-Nordblad, L.; Strandell, H. *Ageing Europe: Looking at the Lives of Older People in the EU*; Publications Office of the European Union: Luxembourg, 2020.
3. Hamano, T.; Tominaga, K.; Takeda, M.; Sundquist, K.; Nabika, T. Accessible transportation, geographic elevation, and masticatory ability among elderly residents of a rural area. *Int. J. Environ. Res. Public Health* **2015**, *12*, 7199–7207. [CrossRef]
4. Iwama, N.; Tanaka, K.; Sasaki, M.; Komaki, N.; Yukio, S. The dietary life of the elderly in local cities and food desert issues: A case study of Mito City, Ibaraki Prefecture. *Jpn. J. Hum. Geogr.* **2009**, *61*, 29–46. [CrossRef]
5. Higgs, G.; White, S. Changes in service provision in rural areas. Part 1: The use of GIS in analysing accessibility to services in rural deprivation research. *J. Rural. Stud.* **1997**, *13*, 441–451. [CrossRef]
6. Stentzel, U.; Piegsa, J.; Fredrich, D.; Hoffmann, W.; Van Den Berg, N. Accessibility of general practitioners and selected specialist physicians by car and by public transport in a rural region of Germany. *BMC Health Serv. Res.* **2016**, *16*, 587. [CrossRef] [PubMed]
7. IMT. *Statistical Yearbook of Mobility and Transport*; IMT: Lisbon, Portugal, 2022.
8. Statistics Portugal. *Life Expectancy at Birth and at 65 is Higher in the North Region*; Statistics Portugal: Lisbon, Portugal, 2023.

9. Alsnih, R.; Hensher, D. The mobility and accessibility expectations of seniors in an aging population. *Transp. Res. Part A Policy Pract.* **2003**, *37*, 903–916. [CrossRef]
10. Reshadat, S.; Zangeneh, A.; Saeidi, S.; Teimouri, R.; Yigitcanlar, T. Measures of spatial accessibility to health centers: Investigating urban and rural disparities in Kermanshah, Iran. *J. Public Health* **2019**, *27*, 519–529. [CrossRef]
11. Casey, M.; Call, K.; Klingner, J. Are rural residents less likely to obtain recommended preventive healthcare services? *Am. J. Prev. Med.* **2001**, *21*, 182–188. [CrossRef]
12. Fujiwara, K.; Osanai, T.; Kobayashi, E.; Tanikawa, T.; Kazumata, K.; Tokairin, K.; Houkin, K.; Ogasawara, K. Accessibility to tertiary stroke centers in Hokkaido, Japan: Use of novel metrics to assess acute stroke care quality. *J. Stroke Cerebrovasc. Dis.* **2018**, *27*, 177–184. [CrossRef]
13. Sahar, L.; Wills, V.; Liu, K.; Fedewa, S.; Rosenthal, L.; Kazerooni, E.; Dyer, D.; Smith, R. Geographic access to lung cancer screening among eligible adults living in rural and urban environments in the United States. *Cancer* **2022**, *128*, 1584–1594. [CrossRef]
14. Beiler, M.; Seketa, B.; Swiatek, W. Investigating transit and pedestrian accessibility for age-restricted communities using spatial analysis. *Int. J. Sustain. Transp.* **2016**, *10*, 881–893. [CrossRef]
15. Masoodi, M.; Rahimzadeh, M. Measuring access to urban health services using geographical information system (GIS): A case study of health service management in Bandar Abbas, Iran. *Int. J. Health Policy Manag.* **2015**, *4*, 439–445. [CrossRef] [PubMed]
16. Yi-Hsuan, T.; Ching-Ju, C.; Hone-Jay, C. Relationship of regional elderly density and bus resource based on geographical analysis. *Taiwan J. Public Health* **2019**, *38*, 252–264. [CrossRef]
17. White, S.; Guy, C.; Higgs, G. Changes in service provision in rural areas. Part 2: Changes in post office provision in Mid Wales: A GIS-based evaluation. *J. Rural. Stud.* **1997**, *13*, 451–465. [CrossRef]
18. Dijkstra, E. A note on two problems in connexion with graphs. *Numer. Math.* **1959**, *1*, 269–271. [CrossRef]
19. Jensen, J.; Jensen, R. *Introductory Geographic Information Systems*; Pearson Education, Inc.: New York, NY, USA, 2013.
20. Bolstad, P. *GIS Fundamentals: A First Text on Geographic Information Systems*, 5th ed.; XanEdu Publishing Inc.: Livonia, MI, USA, 2016. [CrossRef]
21. European Environment Agency. Electric Vehicles. Available online: https://www.eea.europa.eu/en/topics/in-depth/electric-vehicles (accessed on 2 April 2024).
22. Richter, F. Statista, Electric Cars Found to Cut Emissions Drastically. Available online: https://www.statista.com/chart/25412/life-cycle-emissions-savings-of-electric-cars/ (accessed on 2 April 2024).
23. Portuguese Republic; Environment Portugal; Portuguese Environment Agency. *Long-Term Strategy for Carbon Neutrality of the Portuguese Economy by 2050 (RNC2050)*; Portuguese Environment Agency: Lisbon, Portugal, 2019.
24. Zhan, F.; Noon, C. Shortest path algorithms: An evaluation using real road networks. *Transp. Sci.* **1998**, *32*, 65–73. [CrossRef]
25. Yang, C. *Introduction to GIS Programming and Fundamentals with Python and ArcGIS®*, 1st ed.; CRC Press: Boca Raton, FL, USA; Taylor & Francis Group: Boca Raton, FL, USA, 2017.
26. Heywood, D.; Cornelius, S.; Carver, S. *An Introduction to Geographical Information Systems*, 4th ed.; Pearson Prentice Hall: London, UK, 2011.
27. Esri. Types of Network Analysis Layers. Available online: https://desktop.arcgis.com/en/arcmap/latest/extensions/network-analyst/types-of-network-analyses.htm (accessed on 4 April 2024).
28. Shaw, S. Geographic Information Systems for transportation: From a static past to a dynamic future. *Ann. GIS* **2010**, *16*, 129–140. [CrossRef]
29. Tome, A.; Santos, B.; Carvalheira, C. GIS-Based transport accessibility analysis to community facilities in mid-sized cities. *IOP Conf. Ser. Mater. Sci. Eng.* **2019**, *471*, 062034. [CrossRef]
30. Silva, F. Geographic Information Systems for Transportation: An Application to Urban Transport in Guimarães. Master's Thesis, Instituto Superior de Estatística e Gestão de Informação da Universidade Nova de Lisboa, Lisbon, Portugal, 2006. Available online: https://run.unl.pt/bitstream/10362/8444/1/TSIG0012.pdf (accessed on 4 April 2024).
31. Lee, H.; Kim, K.; Kim, N.; Cha, S. Energy efficient speed planning of electric vehicles for car-following scenario using model-based reinforcement learning. *Appl. Energy* **2022**, *313*, 118460. [CrossRef]
32. Zhang, J.; Fan, Q.; Wang, M.; Zhang, B.; Chen, Y. Robust speed tracking control for future electric vehicles under network-induced delay and road slope variation. *Sensors* **2022**, *22*, 1787. [CrossRef]
33. Zhu, W.; Yu, R. Nonlinear analysis of traffic flow on a gradient highway. *Phys. A Stat. Mech. Its Appl.* **2012**, *391*, 954–965. [CrossRef]
34. Zhu, W.; Zhang, C. Analysis of energy dissipation in traffic flow with a variable slope. *Phys. A Stat. Mech. Its Appl.* **2013**, *392*, 3301–3307. [CrossRef]
35. Zhu, W. Motion energy dissipation in traffic flow on a curved road. *Int. J. Mod. Phys. C* **2013**, *24*, 1350046. [CrossRef]
36. Yang, S.; Li, M.; Lin, Y.; Tang, T. Electric vehicle's electricity consumption on a road with different slope. *Phys. A Stat. Mech. Its Appl.* **2014**, *402*, 41–48. [CrossRef]

37. Statistics Portugal. 2021 Census. Available online: https://www.ine.pt/xportal/xmain?xpgid=ine_main&xpid=INE&xlang=pt (accessed on 2 April 2024).
38. Geofabrik. Available online: https://www.geofabrik.de/ (accessed on 2 April 2024).
39. Copernicus Data Space Ecosystem. Available online: https://dataspace.copernicus.eu/explore-data/data-collections/copernicus-contributing-missions/collections-description/COP-DEM (accessed on 2 April 2024).