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A GIS-supported methodology for the functional classification of road networks

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Abstract

The management and monitoring of road networks require constant effort from road owners and managers. This study proposes a decision support method to assist decision makers in planning interventions on road networks. The proposed method supports the functional classification of road networks and their hierarchy using well-defined rules and criteria. GIS tools are used to visualize the resulting classification. The analysis, which does not focus on single roads but on routes composed of one or more roads, proposes a hierarchization based on a set of indicators. These latter describe accessibility, functionality, geometrical and safety characteristics based on which routes can be classified according to different levels of importance. The indicators used are attributable to three main groups. The first group relates to infrastructure connectivity and accessibility; the second to functionality and performance (design speed, homogeneity of traffic flows, etc.) while the third describes the type of road according to variables related to width, tortuosity, accidents, etc. The proposed methodology can support the effective management of road networks and provide road practitioners with useful knowledge elements, also for monitoring road safety.

Keywords: road management; road safety; road hierarchy; GIS

1. Introduction

Road infrastructures impact significantly on the socio-economic, territorial, and environmental development of a particular area. For this reason, they require careful planning and proper management. The study of the relation

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between road networks and the socio-economic framework of transportation networks is a complex task subjected to disciplinary constraints, also in terms of representation. In literature, this study has attracted the attention from researchers across many disciplines, such as transport engineers, urban and regional planners, geographers, architects, environmental scientists, and physicists (Tsiotas, 2021).

Transport networks connect places and serve built-up areas. In network planning, transport planners determine the form of a network not only by adding new network elements but mainly by assigning a function to a road which then influences the road design. Roads with a high share of crossing traffic connecting distant or important places have a different function than urban main roads or urban access roads (Friedrich, 2017).

Street networks are complex objects of investigation and the way we model and represent them as graphs can affect the outcomes of a study (Marshall et al., 2018). There are several related studies in the literature, covering different aims. Among the others, Rivera-Royero (2022) focused on the definitions and characteristics of 11 concepts (including connectivity, redundancy, accessibility, reliability, travel time reliability, vulnerability, etc.) used in the literature to describe road performance, trying to clarify the main differences and relationships between these concepts and giving recommendations about when considering some of them according to the specific planning objectives. Goto et al. (2017) proposed a classification of the road network in Japan with travel speed as a performance measure; the hierarchical road classification is set to achieve the "target travel time" between representative locations defined as "centres".

In transport planning and management, GIS has several potential applications, from maintenance management to accident investigation, safety management, economic impact on the territory, pavement management, etc. It can be used for infrastructure management and monitoring in the road system to assist technological and managerial experts, also for knowledge distribution to decision makers. The use of GIS in road management, particularly for safety issues, allows performing a wide range of spatial analysis and a graphical representation of the results for subsequent interpretation (Rodrigues et al., 2015). GIS has been used to layout the results and show the priority for maintenance and rehabilitation for a network using the critical pavement condition index value (Almuhanna et al., 2018). Many researchers have used GIS tools for assessing road accidents data. In addition, GIS facilitates integration among a database of transport networks and all other socio-economic data, with different planning functions (Singh et al., 2021). GIS capabilities can analyze, query, and modify a road network database and produce useful maps and graphical information (Ribeiro et al., 2019). It allows for a more careful and accurate selection, screening, and reduction of data, and furthermore, allows for spatial analysis of results in pre- and post-processing. Secondly, GIS allows the development of spatial statistics that are based on geographically referenced data (Satria et al. 2016).

To analyze the characteristics of a road network, one must first begin by studying its current condition, then its status over the years and finally its evolution in the future. About the analysis of the current state, the quality of infrastructures can be assessed through numerous types of indicators, not only of physical type, which focus, for example, on temporal data linked to the concept of accessibility.

The role of indicators is fundamental in that they make it possible to evaluate the goodness of infrastructural characteristics, also identifying any deficit compared to other regions, without losing sight of the reference context from which the data and information are derived. The most common indicators focus on specific aspects of the available infrastructure, such as, for example, the amount of public capital expenditure in each period and the length of roads, but often do not provide any information on the quality and adequacy of the service provided. To overcome this methodological and data study limitation, it is reasonable instead to consider indicators based on transport infrastructure assessment, including connection time and distance between territories. In the Bank of Italy's document (2021) on infrastructure gaps, for example, measures of infrastructure endowment are based on transport time and are developed from the analytical tools proposed by the NGE (New Economic Geography). An accessibility indicator is presented, which quantifies the size of the market that can be reached from a given location as a function of its position relative to wealthier or more populous areas. In the case of road transport, the indicator is derived from a comparison of two distinct measures of accessibility:

- the first is calculated, for each starting location, as the weighted mean of the cost of access to all possible destinations; it is expressed by an inverse function of the distance in kilometers from the destination location

- the second is calculated, for each departure location, as the weighted mean of the cost of access to all possible destinations, expressed by an inverse function of travel time relative to the departure location.

The difference between the two measures (times and distances) describes how much the possibilities of reaching the various destinations are modified by the speed of road connections, and provides a qualitative evaluation of the connection possibilities offered by the infrastructure.

The Tagliacarne† Institute points out how the use of a plurality of scale factors (such as population, GDP or surface area of the area in question, etc.) may generate confusion among the territorial classifications of infrastructure equipment, leading to amplification or masking of gaps. In recent years, the Tagliacarne Institute has proposed a scale factor consisting of the average of the surface area (50% weight), population and number of employees, recommending that road infrastructure must be related, preferably, to the area of reference, while point infrastructure, such as ports and airports, to the population served. The choice of scale factor highlights the need to compare the endowments, or rather the offer, with the transport demand, of which GDP, population and geographical area are considered as approximations.

Mention must be made to the importance of updating the population data and the road characteristics database. As they are of an evolving nature, the various basic parameters of the method must be recalculated when significant changes occur.

The study presented in this document was developed with the aim of providing a potential "best practice" to be used whenever a functional classification of a road network is required, assigning a road to a hierarchical level through "rules" and selection criteria linked to specific factors. As an application case, the proposed method is applied to the road network of the Region of Sardinia (Italy) using several official sources to examine the current state of the existing infrastructure, including CNIT (Conto Nazionale delle Infrastrutture e dei Trasporti), ANAS Spa (Azienda Nazionale Autonoma delle Strade) and the Sardinia geoportal.

2. Method and application

2.1 Methodology

The proposed functional classification of the road system can represent an important tool for the correct and efficient implementation of monitoring and management of road networks. It allows to address in a simple and detailed way several issues related to:

- road mobility
- road safety
- road performance
- reduction in the number of accidents and their effects
- mitigation of the criticalities existing in the road industry
- planning and programming of road interventions.

This study defines a macro indicator for the classification of road networks. From the point of view of a graphic representation, this macro indicator can be seen as the sum of three main GIS layers, each representative of a specific sub-indicator:

- the first indicator is representative of connectivity and accessibility, and represents the transport demand, i.e., the relationship between territory and transport.

  Connectivity and accessibility can be modeled using two classification indicators with a functional form such as:

$$I_c = f(x_1, x_2, \dots, x_n) \tag{1}$$

† Guglielmo Tagliacarne Institute, Study Center of the Chambers of Commerce Guglielmo (Italy).

$$I_a = f(x_1, x_2, \dots x_n) \tag{2}$$

Where I_c is the connectivity index and I_a the accessibility index while x_n are the variables related to:

- the number of trips recorded between the provincial capitals and the inhabited centers
- the number of suburban and urban trips for each inhabited center
- the level of service and the extension covered by the highest levels
- etc.

Although a specific functional form for these indicators has not yet been defined, it is known that both indicators are a function of these variables.

- The second indicator is representative of functionality and performance, both attributes are representative of the functional aspects of the transport offer. The parameters considered are:
  - the main traffic attractors distributed in the territory (ports, airports, productive and industrial agglomerations, hospitals, tourist attractors, etc.)
  - the weight of each of the attractors in relation to the reference context
  - project capacity and speed
  - homogeneity of vehicular flows
  - generalized transport cost
  - travel time.
- The third indicator is representative of geometry and safety, i.e., the physical characteristics of the transport offer. Among the parameters considered are:
  - the type of road according to Legislative Decree 285 of 30 April 1992 - New Highway Code
  - width of the road section
  - number of carriageways
  - number of lanes in each direction
  - slope and tortuosity
  - type of movement served.

The three macro indicators are then combined into a larger classification indicator whose quantitative formulation is still in progress. The hierarchization of the road network based on the reported indicators allows to represent the functional role assumed by the different components of the road system while taking into account:

- the functions of territorial economic development that the roads perform in relation to the entire settlement complex (administrative, residential, productive, tourist, and social)
- transport accessibility to interregional integration nodes (ports and airports) and regional territory
- the transport performance and service level (flow, speed, capacity, etc.) they can offer and ensure in relation to the transport demand that characterizes them
- the minimum level of road safety they must guarantee.

2.2 Application

In this study, as an application case, the three proposed indicators are applied to the road network of the Sardinia region (Italy) to identify a new functional classification of its roads that can represent the current and future mobility needs and the socio-economic and tourist needs of the island.

For the application case, existing normative references (regional, national and international) were considered in the review of the current status of the network. The first reference of international scope, through which a hierarchy is made at European level of transport networks, is represented by the Trans-European Transport Networks (TEN-T), that is the set of infrastructures considered relevant at trans-European level (Regulation EU No 1315/2013). At the national level, the regulatory reference considered in the study was the National Integrated Transport System -SNIT (PGTL, 2011), that is, the integrated system of infrastructures that constitute the structure of the Italian mobility offer system for people and goods. Finally, consideration was given to 2008 Regional Transport Plan of Sardinia (PRT), which, among other things, aims to improve functional and mobility relations within the region and between the region and the rest of Italy and Europe.

3. Results

From a graphic point of view, the application of the proposed functional classification method to the Sardinian road network results in a set of GIS layers showing the functional classification of the road network through different maps. As a way of example, Figure 1 shows three overlapping maps, corresponding to as many layers:

a) layer "a" is representative of connectivity and accessibility and reports the number of municipalities that can be reached via the core network

b) layer "b" is representative of the functional aspects of transport supply and reports the number of attractors that can be reached via the core network and the network of regional interest

c) layer "c" is representative of safety and includes the number of road accidents occurring in a given time period on the considered road infrastructures.

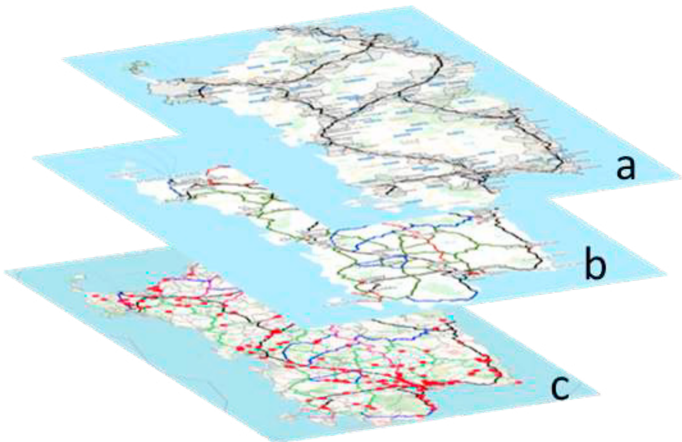

Fig. 1. Exemplification of the overlapping of the different layers

The extra-urban roads of the Sardinian network have been divided into the following three macro-categories:

- **Main network:** it includes all the roads considered of primary importance at national level due to their connection function between the provincial capitals and the main interchange nodes, such as ports and international airports.
  30% of the analyzed road network belongs to the main network, which is mainly characterized by state roads and some important provincial roads. The three main airports of the island (Cagliari-Elmas, Alghero - Fertilia, Olbia-Costa Smeralda) can be reached through this network. As far as hospitals and hospital accommodation are concerned, those directly reachable through the road infrastructures of the main network are 22 for a total of 4,485 beds, of which six allow long-term care and nine rehabilitation facilities. The main network crosses and connects most of the industrial zones of the island.
  If we consider the type of road and the road section that characterize the infrastructures of this hierarchical level, we can say that 70% of the roads are of the main and secondary suburban type with two lanes per direction.

The main network is the network of primary importance thanks to its infrastructural endowment, characterized by the best geometric and performance parameters of the whole Sardinian Road network. It has the function of connection and accessibility between the main interchange nodes and several municipalities of the territory, and allows the fruition of the main hospital and industrial production centers of the island.

- **Network of regional interest** (and national connection):
  - *Level I*: it connects the different provinces and urban centers of interest with the main interchange nodes, completing the main network. Moreover, this hierarchical level includes all the itineraries of particular interest for the socio-economic development of the island in support to production, tourism, and settlement systems.
    The regional first level network is almost composed of secondary suburban roads with a road section between 6 and 8 m (73%), a single carriageway and a single lane per direction. As regards the design speed of the routes that make up the first level of the regional network, more than 66% are characterized by a design speed between 70 and 85 km/h, only 10% have a design speed of 90 km/h. The vehicular capacity, expressed in vehicles per hour, is quite variable in the different road infrastructures that compose the hierarchical level under analysis. In general, 72% of the roads have a capacity between 800 and 1,300 vehicles/hour.
  - *Level II*: it includes the roads that have a role of connection with the provinces and the relative urban system of reference, and/or with the first level network.
    This network makes accessible all those municipalities that are not directly connected to the higher network levels, also providing connections to the first level regional network and the main network.
    Approximately 77% of the network is composed of secondary suburban roads with a medium size road section (between 6 and 8 m), 70% of which can be driven with a design speed between 70 and 90 km/h. These roads have a more significant tortuosity compared to those of the higher-level networks.
  - *Level III*: it includes the internal routes that serve as a connection between the residential centers and the higher-level networks.
    77% of these roads are secondary suburban roads with travel speeds between 40 and 100 km/h, the prevailing speeds are between 60 and 80 km/h. The vehicular capacity, namely the number of vehicles per hour, is quite varied. In general, the prevailing vehicular capacity, is between 1,100 and 1,300 vehicles/hour.
- **Network level of sub-regional and provincial importance**: it is the completing network of the provincial and local network, which must realize the connections of local.

Almost all the roads with separated carriageways fall within the main network. Similarly, the highest design speeds (100-110 km/h) can be reached only on roads belonging to the main level, while 90 km/h can be reached also on roads belonging to the third level. Vehicular capacity ranges from a maximum value of 3,300 veh/h that characterizes 24% of the Main level to 500 veh/h that characterizes 12.3% of Level III (Table 1).

Roads with higher design speeds, namely 110 km/h, are part of the main level. The same applies to design speeds of 100 km/h, while 90 km/h can also be achieved on Level II and Level III roads (Figure 2).

This subdivision allows to highlight how the global system of road infrastructures can be schematized as an integrated set of distinct networks, with different characteristics and functions, both in general terms and with reference to the present case. This procedure was supported by QGIS (OSGeo - Open Source Geospatial Foundation) to allow decision makers to visualize data on maps, tables, and graphs at different levels of detail: road, route, category, type, etc. GIS was used to prepare a map of the study area. This type of output allows the administration to view immediately the overall state of the road network, both as a whole and at a detailed level. In addition, the administration can also explore further subdivisions according to smaller administrative competencies, such as municipalities. This tool is also useful to decision-makers as regards the management of road maintenance and all interventions carried out over the useful life of the infrastructure. GIS made it possible to integrate information relating to:

- characteristics of the single road: type, number of carriageways, number of lanes, design speed, traffic flows, etc.
- location of main port and airport nodes
- location of hospital
- location of relevant industrial areas
- resident population per municipality
- population within certain well-defined areas based on specific characteristics.

Table 1. Vehicular capacity by level.

Vehicular capacity [veh/h]	Main [%]	I level [%]	II level [%]	III level [%]
500	1.49	8.38	1.84	12.32
700	0.00	8.89	4.14	7.77
800	0.34	24.34	10.50	0.20
900	0.06	1.78	15.73	4.79
1,000	3.44	3.54	8.87	7.95
1,100	8.54	13.20	17.58	24.91
1,200	7.94	20.89	31.90	34.40
1,300	8.36	8.72	9.40	5.11
1,500	8.47	10.26	0.00	2.33
1,600	0.00	0.00	0.00	0.05
1,800	1.67	0.00	0.00	0.00
2,400	14.01	0.00	0.00	0.00
2,500	0.22	0.00	0.00	0.00
2,600	1.85	0.00	0.04	0.15
2,900	2.44	0.00	0.00	0.00
3,000	16.96	0.00	0.00	0.01
3,300	24.19	0.00	0.00	0.00

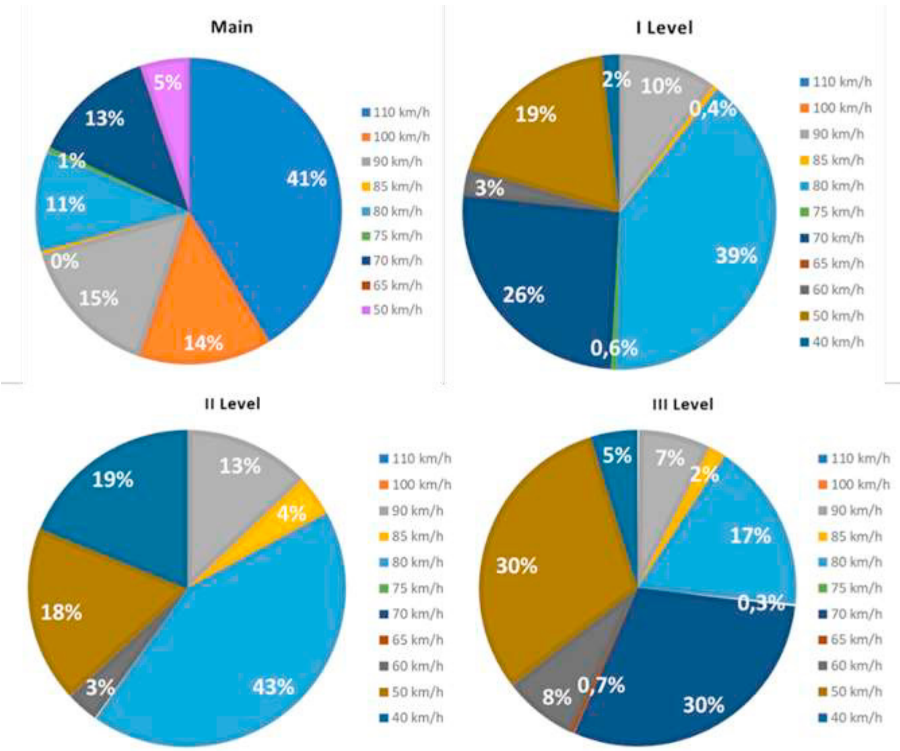

Fig. 2. Percentage distribution of project speeds by hierarchical level.

4. Conclusions

Using a set of indicators describing accessibility, functionality, geometrical and safety characteristics of roads, this study proposed a method for the functional classification of road networks and their hierarchization according to different levels of importance.

As an application case, the methodology was applied to the road network of the Sardinia Region thus identifying three different hierarchical levels, called main network, network of regional interest (divided into Level I, II, III) and network of sub-regional and provincial interest.

The need to perform such a car-oriented classification is strongly related to the regional government necessity to identify within the Regional Transport Plan an appropriate action plan that consider, in the best possible way, the current functional status and use of the current road network, in the light of the new mobility and accessibility needs and the criticalities found in the road infrastructure.

The definition of the proposed classification method is currently in the validation phase, the introduction of new indicators and variables, especially those related to road safety and accidents, is under scrutiny.

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