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ROAD MODELLING FOR INFRASTRUCTURE MANAGEMENT – THE EFFICIENT USE OF GEOGRAPHIC INFORMATION SYSTEMS

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Antonin Pavard, Ph.D.,
Département de Génie de la Construction, École de Technologie Supérieure, Montréal, H3C 1K3, Canada;
Antonin.pavard.1@ens.etsmtl.ca

Anne Dony, Ph.D,
Université Paris-Est, Institut de Recherche en Constructibilité, Ecole Spéciale des Travaux Publics, 28 avenue du Président Wilson, 94234 Cachan, France;
adony@estp-paris.eu

Patricia Bordin, Ph.D,
GeoSpective, 16 B rue Charles Silvestri, 94300 Vincennes, France;
patricia.bordin@geospective.fr

SUMMARY: *The construction sector is undergoing a digital transition. Local authorities have adopted geographic information systems (GISs) to plan their territories and structure their services, such as transport. Simultaneously, building information modelling (BIM) has demonstrated its advantages during the design and construction phases of structures. An infrastructure project can rely on these two technologies to plan its implementation (GIS), to complete its design and construction (BIM), or to manage associated services, such as mobility (GIS). However, road maintenance, an important part of the infrastructure's life cycle, is not yet covered by these technologies. Road maintenance necessitates a comprehensive view of the infrastructure and its interactions with other real-world objects (e.g. vegetation, technical networks, or vehicles). Moreover, road managers are the local authorities that already use GISs. For these reasons, a GIS is suitable for fulfilling road maintenance requirements. This study presents a spatial framework (GIS) developed for road management. Applying it to a specific case study provides insights on the organisation of the spatial road framework which can be adapted to the infrastructure's environment management. The spatial dimension must allow for the representation of the road and its components, including pavements and their dependencies. The structural dimension must be detailed to describe the layers, their formulations, and their thicknesses. The condition of the road must be described concisely so that the managers can plan maintenance.*

KEYWORDS: *road maintenance, modelling, GIS, database.*

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1. INTRODUCTION

The road system is complex with several dimensions (spatial, aesthetic, practical, and political), particularly evident in urban environments where a diverse range of transport modes and equipment networks coexist.

In recent decades, new transport modes have emerged, while old ones such as tramways have been reintroduced. This has prompted a rethink of road systems, particularly in urban areas with a tradition of vehicle-oriented development (Héran, 2015). Today, legislators and planners seek to make different modes of transport interoperable (Héran, 2017) by reorganising roads to meet various needs (Augello, 2001). This transformation involves an increasing number of planners and urbanists in projects. In addition to transport, roads also accommodate equipment networks, for example, technical networks for water, sanitation, gas, electricity, telecommunications, or geothermal systems. Some of these facilities were initially installed under the road (water, sewerage, or gas), while others were historically deployed overhead (electricity or telecommunications). However, some countries have since opted to reposition their technical networks underground for various reasons (e.g. aesthetics, safety, or climate). As a result, the ground beneath roads is now densely occupied, with some Parisian crossroads having up to thirty technical networks (Barles and Guillerme, 1994).

Both modes of transport and technical networks rely on roads to provide their services, utilising infrastructure or equipment installed on top of or underneath the roads that interacts with and affects their surface and structure. For instance, the weight, speed, and trajectory (tangential force) of a vehicle affect roadways (Pais et al., 2013), known as traffic loading. Engineering networks also have negative impacts on roads. Zimmerman (2002) stated that the co-presence of technical networks could lead to incidents, risks, and several repercussions on urban infrastructures and populations. Network impacts on roads are direct when a water pipe leaks and erodes the road structure; they are indirect during excavation intervention for their maintenance. Excavation and backfilling reduce the service life of a road by 50% (Aljr, 2017; Jensen et al., 2005). The challenging coordination of actors results in premature road deterioration, necessitating more frequent maintenance actions, which has an impact on managers' budgets and wastes resources like aggregates, bituminous, or hydraulic binders. GIS tools can help to improve the coordination of actions on road infrastructures.

This article proposes to develop a GIS-based spatial framework for managing road infrastructure and its environment. The research methodology is presented in three parts. Firstly, the rationale for using GIS is explained. Then, the modelling approach for creating the spatial framework is discussed. Finally, the scope of the research is defined with a clear definition of the urban road. The subsequent sections focus on the spatial framework and its development through analysis of existing GIS models of roads, with the authors selecting the horizontal dimension (geographical footprint) and the vertical dimension (road structure and condition) for modelling. The last section of the article presents an application of the road spatial framework to a case study in the municipality of Cachan in the south of the Paris metropolitan area. This case study demonstrates the framework's applicability and usefulness for managing road infrastructure in its environment.

2. RESEARCH METHODOLOGY

2.1 Background

Roads have a limited service life, and their deterioration is caused by various factors, which can be prevented through regular maintenance (Sauterey and Autret 1977). Without proper maintenance, roads will deteriorate and eventually become unusable (George et al., 2019; Smith et al., 1993). To ensure proper maintenance, comprehensive and up-to-date information is essential (Faivre d'Arcier et al., 1993). In 2017, the French government set two objectives to increase knowledge of roads and improve communication between different actors involved in road management (Ministère de la Transition écologique et solidaire, 2017). Many countries in Europe and North America have also developed road maps to outline the digitalisation of transport structures (Borrmann et al., 2021). While the deployment of BIM for infrastructure is useful for managing structures such as buildings, its deployment for transport infrastructure remains complex due to several barriers (Ghasemzadeh et al., 2022). However, Garramone et al. (2020) demonstrated that the integration of GIS and BIM could benefit the management of infrastructure such as roads. A GIS provides a geographic repository to integrate infrastructure into its environment and powerful spatial analysis tools for works management.

Since their emergence in the 1960s, GISs have garnered significant global interest for their ability to study real-world objects in interaction with their surroundings. However, defining a GIS can be challenging due to the diversity and wealth of approaches involved (Maguire, 1991). According to the authors, a GIS can be described using three dimensions that remain relevant today. Firstly, a GIS facilitates the representation of real-world objects through maps. These objects are depicted using vector graphics (points, polylines, and polygons) or raster graphics (cells) organised into different layers based on the nature of the geographic and graphic objects. Secondly, a GIS employs a sophisticated database management system (DBMS) to perform analyses based on attribute data, such as selecting real-world objects based on specific parameters. Finally, a GIS provides a spatial framework in which real-world objects are located and represented in an absolute manner using coordinates (x, y, and z). It is possible to carry out complex analyses by combining the cartographic and database aspects of GIS, a process known as spatial analysis.

Various fields related to transport and land use planning identified the potential of GISs to address business problems at an early stage. Experts in road networks, particularly in transport flows, sought to model road traffic. With the help of road data organised in the form of transport graphs, GISs enable the use of graph theory (Fournier and Pomerol 2010) and characterise traffic by measuring accessibility, for example, by the shortest route. This work has led to applications in other areas such as urban planning and development, to optimise the organisation of services and territories (Murray, 2013; Chalkias and Lasaridi, 2009), or geomarketing, to optimise the location of a company or business (Church and Murray, 2008). The representation of real-world objects in their environments has made it possible to deal with other aspects such as noise and air pollution (Li et al., 2002; Rebolj and Sturm, 1999) induced by road traffic. Later, GISs were used to analyse the outcome of traffic accidents (Shahzad, 2020; Satria and Castro, 2016).

In summary, GISs were initially applied to transportation, including roads, to tackle issues related to road services. With the digitalisation of the construction industry, GISs have been integrated into several phases of construction projects. GISs are highly effective in this sector as they integrate both spatial and non-spatial project information in a single environment (Bansal, 2007). The main lines of research conducted for the integration of GISs in construction practices are summarised in Tab. 1.

TAB. 1: Main research areas for the integration of GISs in the construction process (Pavard, 2023).

PH.	USES	AUTHORS
DESIGN	✓ Simulating the implementation of a new construction, with multi-criteria approaches (the diversity of the environment)	(Mike et al., 2022)
	✓ Choosing the most suitable location according to the topography, the nature of the soil, or the natural risks	(Kumar and Bansal, 2016; Mallick et al., 2014)
	✓ Analysing the visual impact of a future construction o The emergence of the third dimension in GISs reinforces this	(Llobera, 2003) (Cheng and Chen, 2002)
CONST.	✓ Improving worker safety or waste management	(Li et al., 2005)
	✓ Optimising procurement	(Jadid and Idrees, 2013)
	✓ Assisting construction projects: with its ability to store geographic and non-geographic data, and by combining spatial databases with planning tools to monitor the construction process	(Bansal, 2020; Bansal and Pal, 2006) (Cheng and Chen, 2002)
MANAG.	✓ Helping to understand infrastructures through enriched spatial data	(Zhang et al., 1994)
	✓ Helping to manage infrastructures through an integrated vision that places infrastructures in their environments	(Ferreira and Santos Duarte, 2006)

The research presented in this article is part of a road infrastructure management approach. Consequently, an integrated GIS for road infrastructure management requires a four-tier architecture: (1) the GIS interface tier, (2) the application tier, (3) the infrastructure management component tier, and (4) the data/knowledge repository tier (Halfawy et al., 2002). The issue of data and knowledge is crucial, as without it, no integrated GIS can be realised. Some researchers have assumed that the development of data and knowledge for road GISs will be achieved through the development of interoperability between computer-aided design (CAD) and GIS tools (Peachavanish et al., 2006). This implies that road information exists in CAD formats, but this is not always the case as roads are rarely modelled in spatial frameworks suitable for infrastructure management. Moreover, older roads are rarely modelled in BIM. Currently, this type of GIS is implemented through local initiatives, and the municipalities that are driving this field do not have a standard framework. Other municipalities that wish to undertake similar initiatives face many questions, such as what and how to model, and what and how to enrich the data.

2.2 Research scope: urban roads

While all roads support mobility, there are notable differences depending on road type. Motorways do not support the same mobility as local roads, resulting in different traffic flows, modes of transport, and management strategies. Motorways and national roads are under national jurisdiction, with their management focused on safety strategies related to the high volume and speed of traffic. Local roads, by contrast, are mostly under municipal jurisdiction, with managers striving to optimise safety for different users while maintaining the activities of the city. It is therefore important to specify the scope of this research. Local roads may be either urban or non-urban, but managers have limited information about them. Urban roads make up the most complex system, as they are used by a diverse range of activities including soft modes of transport, such as scooters and bicycles, and more aggressive modes, such as cars and lorries. In addition to mobility, urban roads also support leisure activities such as festivals, craft markets, and restaurant or bar terraces, as well as activities related to city management, such as car parks or delivery spaces.

By analysing regulatory and technical documents, two aspects can be identified to define urban roads: regulatory and technical. The regulatory aspect of this definition is specific to the French context. French road legislation, like that of many Western countries, traces its origins to Roman law. Therefore, the definition shown in Fig. 1 applies to many cases: *The (urban) road is an infrastructure that allows land traffic but not rail traffic. It passes through a built-up area and is either a public or private asset belonging to a local authority, or an individual or group of individuals* (Pavard 2020).

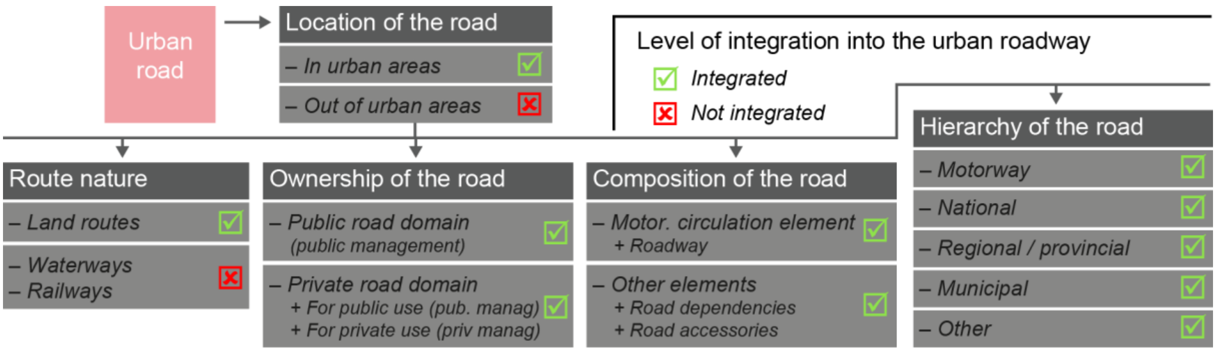

FIG. 1: Urban road according regulatory issues (adapted from Pavard, 2020).

Compared with technical literature from other European and North American countries, French technical literature provides a definition of the technical dimension of urban roads (Fig. 2). Urban roads consist of *a central element, a roadway, and related dependencies and accessories that enable its maintenance, ensure user safety, and provide for its arrangement* (Pavard 2020).

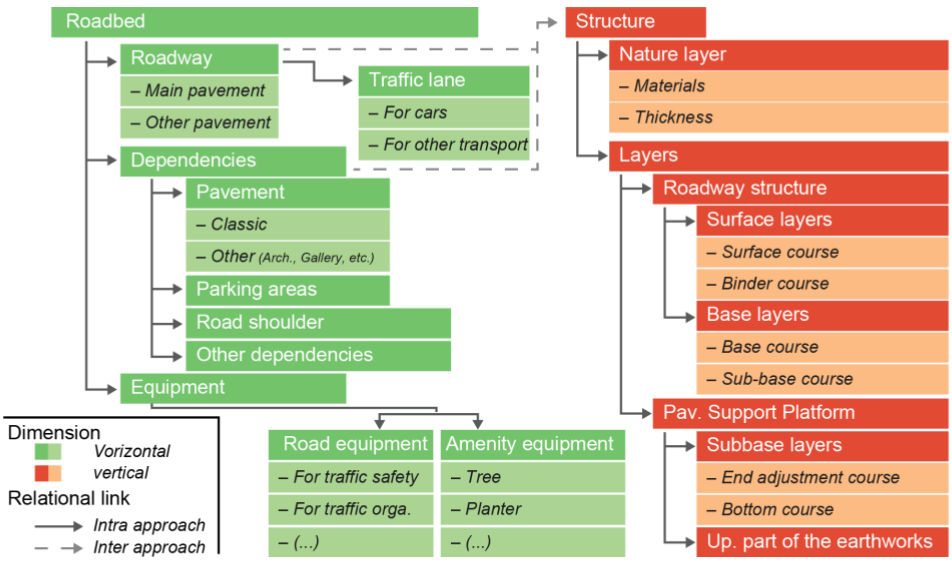

FIG. 2: Urban road according technical aspects (adapted from Pavard, 2020).

2.3 Research method: Modelling approach by accompaniment

This research is part of a series of studies initiated in 2013 to optimize of joint road and environmental management, including technical networks, using geomatics. The objective is to develop a spatial framework for roads and to provide recommendations for road modelling in GISs (Pavard, 2020). To achieve this, an iterative and collaborative approach was adopted, based on the principles of accompanying modelling (Etienne 2010; Bousquet et al. 2013). This approach, which was developed in 1996, facilitates collective decision-making processes and helps to make explicit the subjective viewpoints and criteria of various stakeholders. Its creators emphasised that in complex situations, decision-making processes are often evolutionary, iterative, and continuous. As a result, decisions may be imperfect, but they can be improved and better understood with each iteration. The aim of this method is not to improve the quality of the choices made, but rather the quality of the decision-making process. It primarily aims to enhance the management of uncertainties in a given situation. The approach is based on three precepts:

- Acceptance and consideration of sometimes contradictory viewpoints
- Questioning of each new element introduced into the process
- Confrontation with each new external element.

The approach is composed of three main elements: stakeholders, tools, and models (Etienne, 2010). Given that the aim is for the approach to be applied in a real-world environment, it is first presented to a diverse range of stakeholders concerned with the object of study. Therefore, it is stakeholder-oriented and divided into four groups: researchers, technicians, institutions, and non-professionals. Each group offers a complementary perspective and is important for model confrontation:

- **Researchers** possess organised and validated academic knowledge. This group comprises researchers in areas such as road materials, geographic modelling, and urban infrastructure management.
- **Technicians** possess knowledge that is primarily based on the study of a large number of situations and specialised technical data. This group includes technicians and engineers in civil and urban engineering, spatial modelling (GIS), and building modelling (BIM).
- **Institutions** have a political and economic understanding of the system. This group consists of road managers at different levels (municipal and departmental).
- **Non-professionals** have knowledge derived from empirical experiences. This group includes students in civil engineering and spatial modelling (GIS) or building modelling (BIM).

Regarding the tools used in the approach, its initiators argue that the field of cognitive sciences and computer science have a tool that is particularly suited to the study of complex and dynamic systems: multi-agent systems (MASs). In this context, MASs balance the more conventional tools of geomatics by formalising the dynamics and hypotheses under study (Collectif ComMod 2005).

For this research, the primary focus was not on studying hypotheses related to road management or other dynamics, but rather on proposing a model of the road in its environment, in order to provide managers with a suitable representation tool for the challenges faced by the road. Therefore, the approach is based on accompanying modelling and the least appropriate steps are avoided. For example, MASs are less usefull for this research than conventional tools of geomatics. The steps proposed by Barnaud et al (2007) are followed and adapted to the research context (Fig. 3).

To complete specific steps of the accompanying modelling process, specific case studies were relied upon. These case studies involved the following:

- Understanding the initial situation of road infrastructure modelling in GISs. This constitutes the first step of the approach. To achieve this, study areas with road data that reflect the diversity of existing modelling approaches were covered. Various cases were identified, including French cases, such as Paris, Bordeaux, and Lyon; European cases, such as Copenhagen in Denmark; and North American cases, such as Montreal and Victoria in Canada and San Francisco in the United States. For the purpose of this article, additional cases were included, such as Repentigny and Moncton in Canada.
- Producing modelling proposals adapted to the problems identified in the first step. This is the second step of the approach. To validate the model, it is easier to perform this step on a case that is easily accessible, making it possible to compare the results with reality. In this regard, the municipality of Cachan, located in the southern part of the Paris metropolitan area, was chosen.

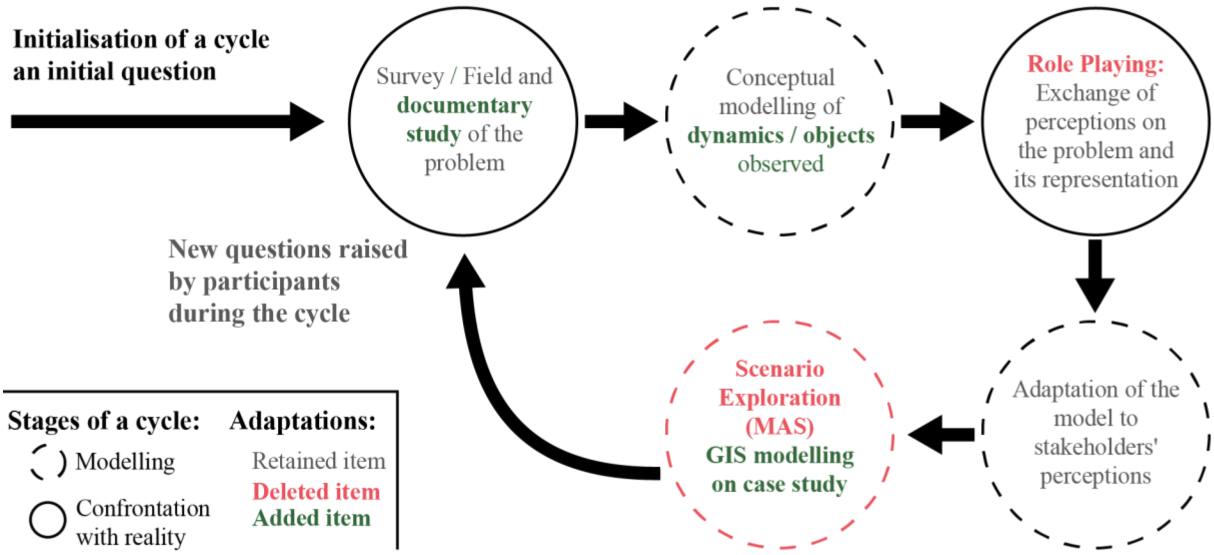

FIG. 3: Adaptation of the accompanying modelling cycle (from Pavard, 2020).

3. DESIGN OF A SPATIAL FRAMEWORK ADAPTED TO ROAD INFRASTRUCTURE MANAGEMENT

Different stakeholders in urban road infrastructure have varying perspectives on what the infrastructure is and what it is used for. As a result, different road models are created. For instance, specialists in road traffic concentrate on traffic routes, while urban planners focus on above-ground structures. Civil engineers, for their part, are more concerned with the underground layers that constitute the infrastructure. Based on these road models, experts in geomatics develop geographic databases that can be used in GISs. The following sections present a classification of the key databases used to represent roads, an identification of the most suitable one for infrastructure management, and a proposal for a data model.

3.1 How to model roadways and dependencies?

The various road models and representations in GISs (Fig. 4) are designed to address two specific needs: managing the movement of people and goods (Fig. 4a & Fig. 4b) and managing the space (Fig. 4c & Fig. 4d).

Modelling	Initiative	Road elements	Management: Transport	Management: Spatial	Management: Infra-structure	E.g. databases
(a)	National or Local	☒	☑ (green)	☒	☒	Several road DB at a min. scale of 1:10,000 - like IGN BD TOPO (France)
(a)	Local	☑ (orange)	☑ (green)	☑ (orange) if data on the width of pav. & sidewalks	☑ (orange) if data on the structure	Road DB: - Lyon (France)
(b)	National or Local	☑ (orange)	☑ (green) Multimodal	☒	☒	Combination of DB from several modes of transport
(b)	Local	☑ (orange)	☑ (green) Multimodal	☑ (orange) if data on the width of pav. & sidewalks	☑ (orange) if data on the structure	Road DB: - Quebec (Canada)
(c)	National France	☑ (green)	☒	☑ (orange)	☒	Plan Corps de Rue Simplifié (PCRS) - Bordeaux (France)
(d)	Local municipalities in Europe and North America	☑ (green)	☒	☑ (green)	☑ (green) if data on the structure	Road DB: - Paris & Bordeaux (France) - Copenhagen (Denmark) - San Fransisco (USA) - Montreal, Victoria & Moncton (Canada)

FIG. 4: Summary of models and road representations (Pavard, 2023).

However, some municipalities have recognised the need to develop a GIS-based process for managing their road infrastructure. To achieve this, local initiatives have focused on designing a suitable road framework. Through analysing these initiatives, two main aspects have been identified:

- The ability to identify the different elements of the road (roadways, appurtenances, and equipment)
- The ability to measure the right-of-way of each road element.

These local initiatives have used existing road models and representations. For Lyon (Fr), roads are modelled by the axis of their main roadways, assuming that each section has a uniform roadway width and pavements on either side with uniform widths (Fig 4a); this is unlikely to be the case in most urban areas. Quebec (Ca) has a similar solution, but with separate models for the roadways and pavements, taking into account possible discontinuities (Fig. 4b). Bordeaux (Fr) started by using a boundary approach to model the road (Fig 4c). This approach is the result of a process of producing a simplified street body plan (Plan de Corps de Rue Simplifié – PCRS), i.e. a topographic framework at a scale of 1/200th that allows the positioning of objects occupying urban space (e.g. technical networks) in relation to road elements (CNIG and AFIGEO 2017). Other cities like Paris (Fr) (Mairie de Paris - Division des plans de voirie, 2011), Copenhagen (Dk), San Francisco (USA), Montreal (Ca), Victoria (Ca), and Moncton (Ca) have focused on modelling road rights-of-way. The models vary in their comprehensiveness, with some only distinguishing between roadways and pavements and others modelling all road elements (Fig 4d).

The last model (Fig. 4d) is the most appropriate for establishing a road spatial framework useful for global infrastructure management. It enables:

- the measurement of the right-of-way of the road and its running sections;
- the identification of the different road elements according to the completeness of the modelling.

3.2 How to model crossroads?

The different GIS models and representations (Fig. 5) are designed to meet two specific needs: understanding of the road system in a given territory and managing infrastructure. Through analysis of the data models and resulting databases, two aspects of crossroad modelling are identified:

- The ability to distinguish between crossroads and road sections
- The limits of the “crossroad” to be included in a modelling approach that is suitable for infrastructure management.

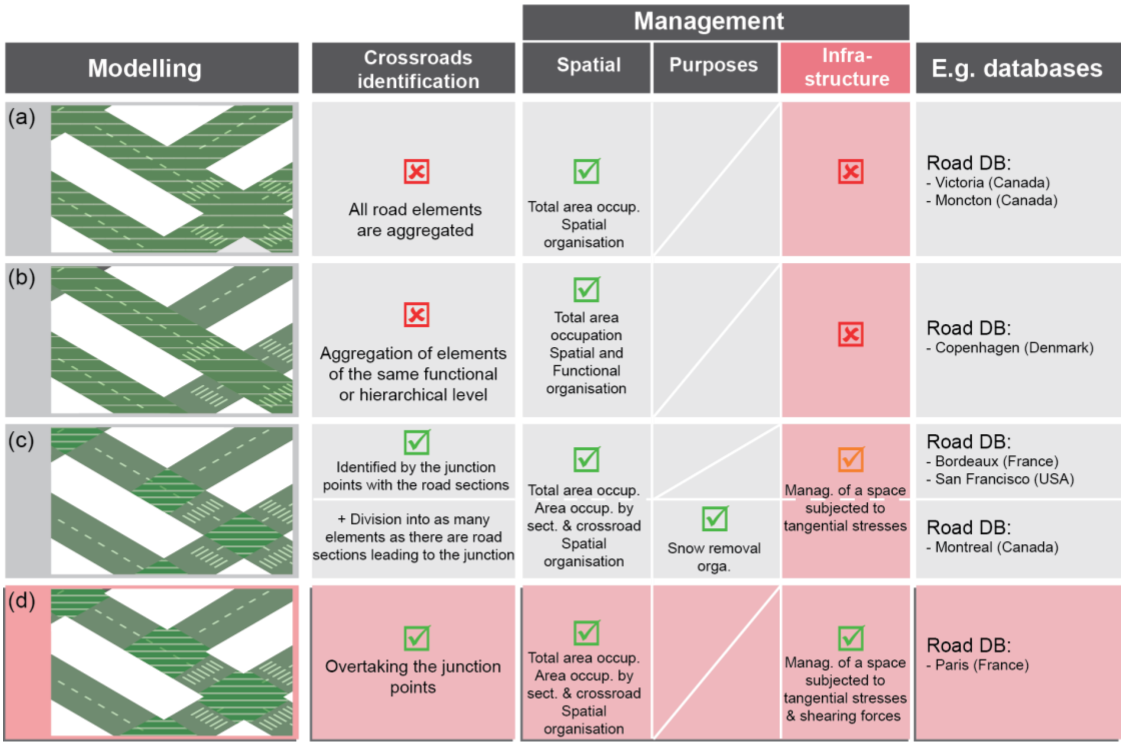

FIG. 5: Summary of models and crossroads representations (Pavard, 2023).

The various initiatives are based on models to answer specific questions. Victoria and Moncton (Ca) model their roads without distinguishing between road sections and crossroads, represented by a single polygon (Fig. 5a). This is useful for understanding the overall organisation of the road in a territory. Copenhagen (Dk) proposes a variant that analyses organisational differences based on road hierarchy (Fig. 5b). Lyon (Fr) and San Francisco (USA) model and represent crossroads separately from road sections using junction points (Fig. 5c). This provides information to manage these spaces structurally, including tangential stress. Montreal divides crossroads into as many road sections that lead to them, according to the road department, for snow removal purposes. The division of crossroads is interesting to make the surface objects of the designed spatial framework consistent with the linear objects of other road spatial frameworks (see Fig. 4a, p.7). Paris (Fr) models crossroads and spaces on each road section upstream of the crossroads, taking into account shear forces (Fig. 5d).

Crossroads are subject to mechanical stresses related to vehicle movements and the distribution of loads on the pavement when vehicles turn, causing tangential loads (Hamlat 2007). Researchers have shown that pavement shearing also occurs due to vehicle deceleration and acceleration near crossroads. Hammoum et al (2010) identified that the maximum horizontal forces during acceleration occur within the top 10 metres of the roadway, while Akcelik and Besley (2001) found that horizontal forces have a greater impact during deceleration. Considering braking distances based on vehicle weight, the most affected area is between 30 and 70 metres from the crossroad. Crossroad design aims to resist these stresses, but the upper part of the roadway structure ages more rapidly than the rest of the road sections. Therefore, it is essential to have information on crossroads for road management. The choice of modelling method used by Bordeaux (Fr) is mostly based on the technical means available to the municipality. Nevertheless, recent methods (Cura et al., 2018) may eventually make it easier to implement the more operational modelling of road spatial frameworks for infrastructure management. That is why, the last model (Fig. 5d) is the most appropriate for establishing a road spatial framework useful for global infrastructure management.

3.3 Summary in a data model

A straightforward data model is suggested (Fig. 6) that can be customised to meet the specific needs and available resources (financial, human, and technical) of municipalities responsible for road management. This model consists of three priority levels:

- The first level comprises the essential elements to be included, namely the road sections and crossroads that consist of pavements and sidewalks.
- The second level involves the incorporation of supplementary elements, such as other structures.
- The third level entails the inclusion of the pavement equipment and other structures.

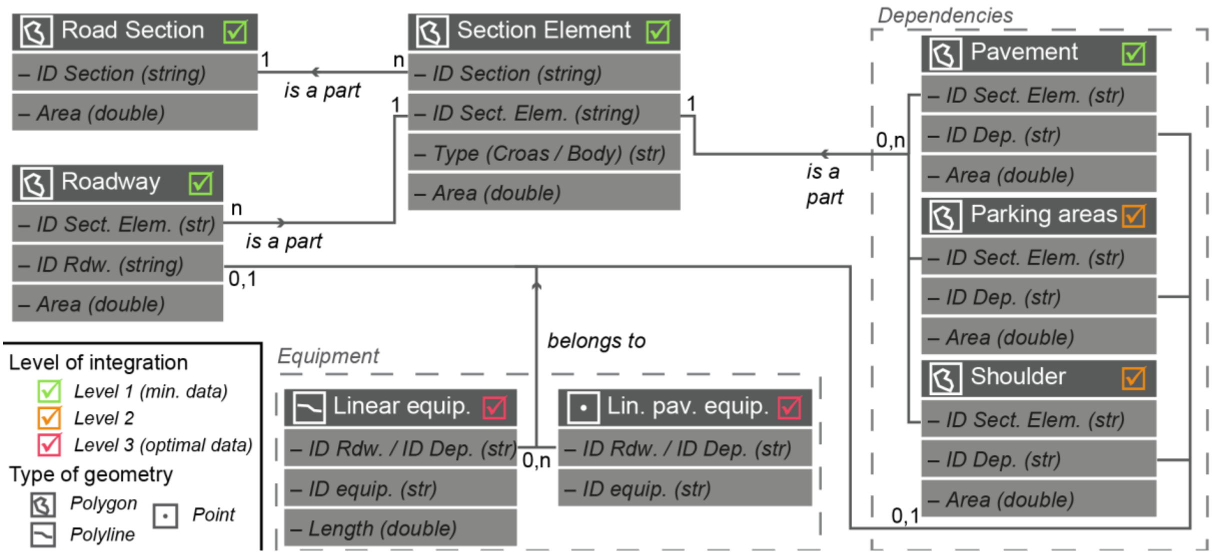

FIG. 6: Data model of an adaptive spatial road framework (adapted from Pavard, 2020).

4. ENRICHMENT OF THE ROAD SPATIAL FRAMEWORK

Road elements are designed to withstand the stresses caused by their intended use. Indeed, specific rules must be followed to consider mechanical stresses from factors like road traffic. The design process involves calibrating the various layers of the infrastructure (Fig. 7) by selecting appropriate materials and determining the optimal depth for each layer (IDRRIM, 2020; LCPC and Setra 1998). For example, heavy vehicles passing over roadways cause significant wear and tear, so requirements for roadways differ from those for bicycle paths or pavements. Proper consideration of traffic loading and climatic stresses helps ensure the durability of each structure over its lifespan. It is worth noting that road infrastructure occupies not only the surface but also a significant underground volume, making it important to enrich the spatial framework with data about road structures and conditions.

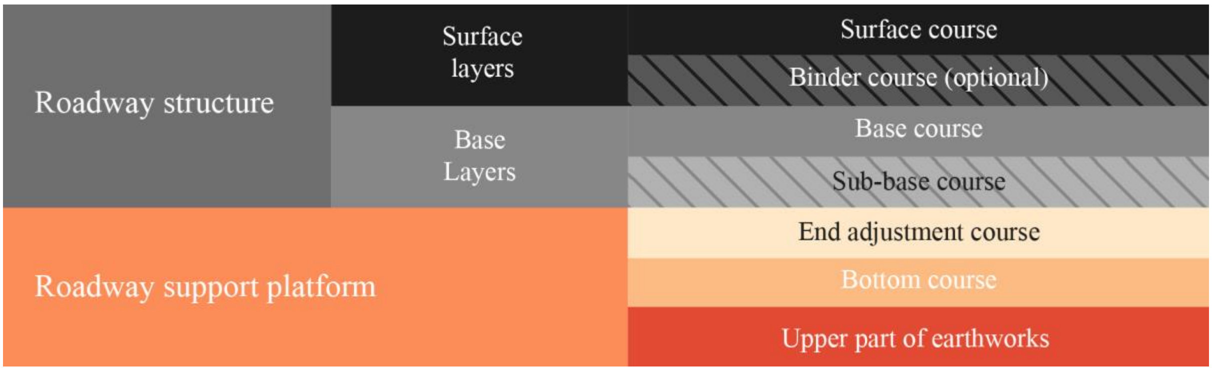

FIG. 7: Typical roadway structure (adapted from Pavard, 2020).

4.1 How to describe the structure?

Examples of municipal GIS data indicate limited integration of the underground dimension of road. However, some municipalities are taking the lead in developing a process that is suitable for managing the entire road infrastructure. These initiatives have resulted in two levels of structure integration:

- the first level only takes into account the top layer, known as the surface course;
- the second level includes all layers of the infrastructure as well as its support.

Analysis of local initiatives reveals that:

- Information on surface layers is typically available, but it is often in general categories such as concrete or asphalt. For example, the 2019 version of the Repentigny (Ca) database proposed this description (Fig. 8a).
- Information on complete structures is typically provided for roadways, either in a general classification (Montreal) (Fig. 8b) or a more detailed classification (Lyon) (Fig. 8c). Detailed material information is generally absent.

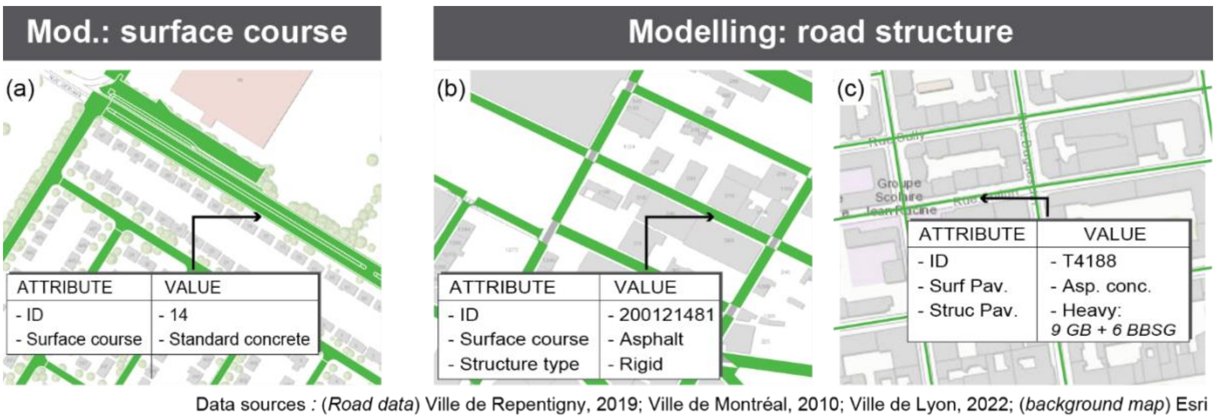

FIG.8: Description of the road structure, example of Montreal (Canada) (Pavard, 2023).

Surface information has several advantages for managing a city's roads: it helps to ensure harmony between spaces and ensures the safety of users through appropriate space separation (Reigner 2004); it is also essential for addressing heat island issues (Stempihar et al. 2012; Hendel et al. 2015) and noise pollution (Li, 2020). However, this information is not enough for the infrastructure's environment management.

To better understand the information needs for road structures, an analysis was conducted on the technical literature. Most national agencies responsible for road studies produce technical guides that outline the stages and parameters used for design (LCPC and SETRA 1994). Municipal road guides provide specific information on the choice of surface materials based on local conditions. These documents are part of a strategic approach to investing in and maintaining urban roads. A qualitative textual data analysis was carried out on the French case, based on national and local technical documentation from large municipalities, and from this analysis a list of information necessary for the management of surface materials and structures was compiled.

When it comes to surface materials, their management depends on several factors as indicated in the local technical documentation. These factors include the modularity of the material, whether it is modular (such as pavers) or non-modular (such as asphalt), the available surface area, the performance of the material (such as reparability, cleanability, and cost), and the type of surface activity (motorised or non-motorised). In terms of structures, their management depends on various factors including the intended service life as per the design, mechanical aspects related to traffic and soil bearing capacity, thermal and hydric aspects related to weather conditions, and human factors related to external interventions, such as the installation and maintenance of new networks (e.g. electrical, telecom, or geothermal). These parameters have been translated into data that can be collected from existing documents or databases (Tab. 2).

TAB. 2: Summary of design criteria, e.g. France (adapted from Pavard, 2020).

PART OF THE STRUCTURE	PARAMETERS	EXISTING DATA
SURFACE AND BASE LAYERS	• Modularity, performance	• Local technical guides
	• Space constraint	• Available from the proposed road spatial framework
	• Use property • Service life	• Design project document
	• Traffic: nature, class, progression, traffic loading	• GIS DB Road graph
	• Freeze-thaw index.	• GIS DB climatology
	• Other infra. (i.e. technical network)	• Other GIS DB
SUPPORT PLATFORM	• Geotechnical classification of natural soils	• GIS DB Soil
	• The bearing capacity class.	• Depends on the nature of the soil

4.2 How to describe road damage?

After construction, roads deteriorate due to various factors such as ageing due to climatic cycles, mechanical stress, or buried technical networks requiring trenching. To plan road management on a territorial scale, having information on road conditions is essential. Responsibility for managing the condition of roads in municipalities falls under the jurisdiction of a dedicated road department, which conducts inspection campaigns. However, the data produced from these inspections are often poorly integrated into GIS. This discussion examines modelling approaches for damage and the relevant data required to describe it within a road spatial framework. The French case is used as an example.

In France, the technical guide for analysing road damage dates back to 1998 (LCPC 1998). The guide does not provide a detailed description of the damage; however, it does categorise it into two main types: structural damage corresponding to permanent deformations, and surface damage. These types of damage can be characterised spatially. The French national road observatory (ONR) has identified two monitoring methods and their main applications (IDRRIM, 2018 and 2019):

- Visual inspections involve analysing the roadway condition through manual observation by an operator. They are preferable for assessing surface conditions.
- Automatic surveys involve analysing the roadway condition using surveys conducted automatically by algorithms. They are preferable for identifying structural damage.

The data produced by these collections are raw and ill-suited to comprehensive road infrastructure management. The emergence of new monitoring tools since the early 2010s (Wasner, 2019; Hornych et al. 2016) has only reinforced this issue. These tools can now monitor the road to the thousandth of a millimetre, with some recording 3D images of roadway sections between 2.5 to 10 metres in length. These images can automatically detect most areas of structural and surface distress. However, the use of these detailed data presents several challenges when working within a road spatial framework. Firstly, these data are voluminous and their storage requires extensive resources. Secondly, the sheer amount of data makes analysis and updating difficult. When enriching their spatial road frameworks with distress data, municipalities often choose to summarise the information in a "condition" index. This information allows them to prioritise interventions based on the level of damage. However, it may obscure the reasons behind a road's deterioration.

The lack of a suitable monitoring process for urban roads makes it challenging to identify road damage data to integrate into a spatial reference system for roads. In France, the Directorate of Roads has developed a system to evaluate and monitor national roads. This system is based on three scores describing the road sections broken down into portions of 100 to 200 metres (Setra 2000). This corresponds to the *Image de la Qualité du Réseau Routier National* (IQRN), and some departments have adapted this system into the *Image de la Qualité des Réseaux Routiers Départementaux* (IQRD) (IDRRIM 2017). They removed certain tests, such as roughness for skid resistance or segmentation from 100 to 200 metres, and used an operating procedure more suitable for low-traffic roads and for crossing urban areas (LCPC 1997). A report by the ONR shows that the methods developed at the national and departmental levels are not compatible with the municipal level. Indeed, the municipal level has specific characteristics, whether in terms of roadway size, layout, surface occupancy, or traffic (IDRRIM 2017). A national research programme on roadway service life (DVDC) aims to improve methods for monitoring roads. In the long term, it will promote the development of roadway testing doctrine and produce new indices to better describe the condition of urban roadways. While waiting for the results of this project, it is possible to include information on road distress by using methods of aggregating road distress by type (Fig. 9a) or aggregating their enclosing rectangles (Fig. 9b).

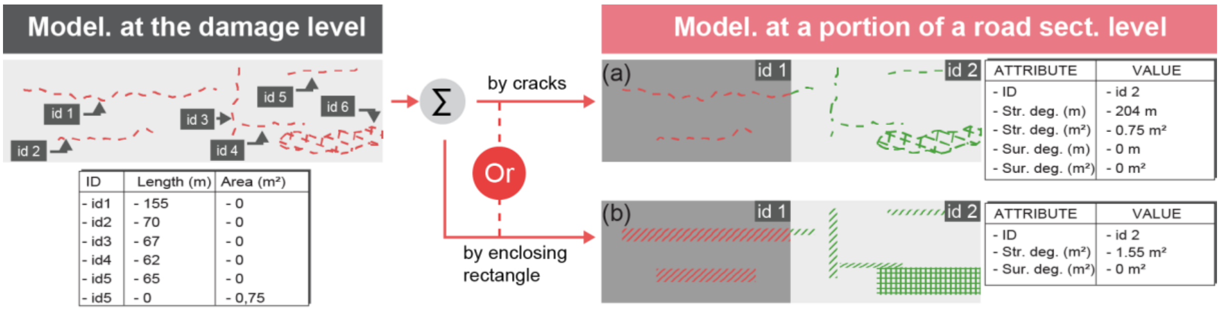

FIG. 9: Road deterioration (adapted from Pavard, 2020).

Furthermore, some recommendations can be followed:

- Since damage has different causes, knowing the type of damage makes it possible to better plan interventions (Pavard, 2020, pp. 208-210; Sauterey and Autret, 1977).
- Precise monitoring of each element of damage requires significant resources and heavy data management. Managing information on damage in an aggregated way is recommended.
- Many local interactions have an impact on the integrity of the urban roadway. Maintaining a segmentation of the roadway is recommended to reduce the granularity of the analysis. Based on the standards of new technologies, a step size of 10 to 50 metres can be retained.

4.3 Summary in a data model

The recommended enrichment of road spatial frameworks with data on the road structures and damage is accomplished through descriptive attribute tables (Fig. 10):

- One table describes the structures of the road elements.
- One table describes the materials, consisting of sub-tables providing information on modularity, performances, property uses, or space restrictions.
- One table describes the damage to the road elements, including information on auscultation campaigns, observed damage, and the causes.

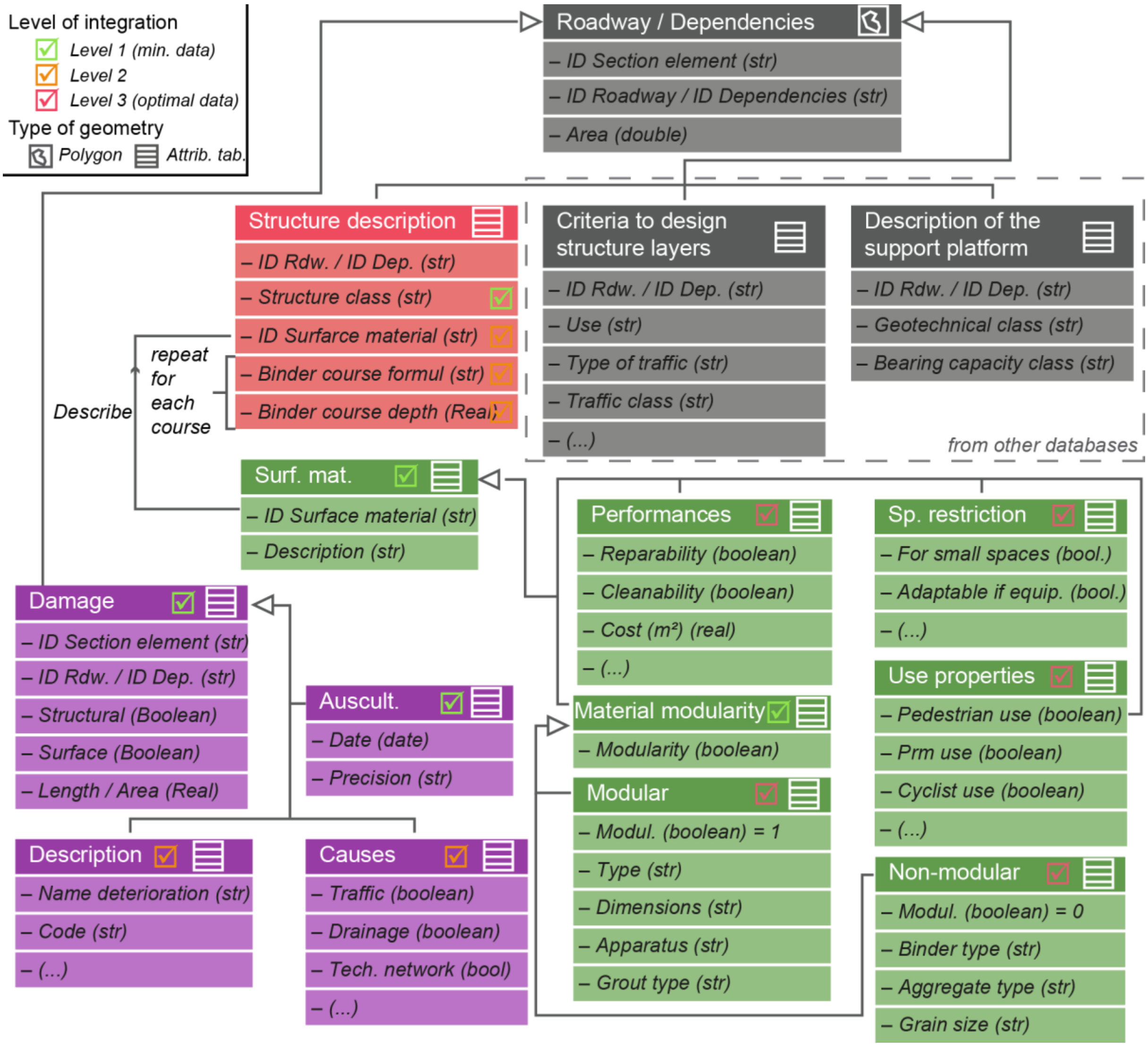

FIG. 4: Data model for enrichment framework (adapted from Pavard, 2020).

5. FRAMEWORK APPLICATION ON A STUDY CASE

The application of the process for constructing the road spatial framework in a case study demonstrates the feasibility and usefulness of the spatial framework for addressing global management questions related to road infrastructure (Pavard et al., 2022). Cachan (Fr) was selected for its location and diverse urban roads, including road facilities (roadways, equipment, crossroads), road elements (outbuildings, pavements), and road types (motorways, main roads, and secondary roads). Due to limited technical and human resources, the construction and enrichment of the road spatial framework were also limited (Fig. 11):

- Regarding the construction of geographical data, crossroads were not delineated, and road equipment was not integrated, except for vegetation.
- Concerning enrichment, structural data were limited to surface information, and damage was counted but not measured.

Processes were developed for less advanced municipalities for each phase in constructing and developing frameworks.

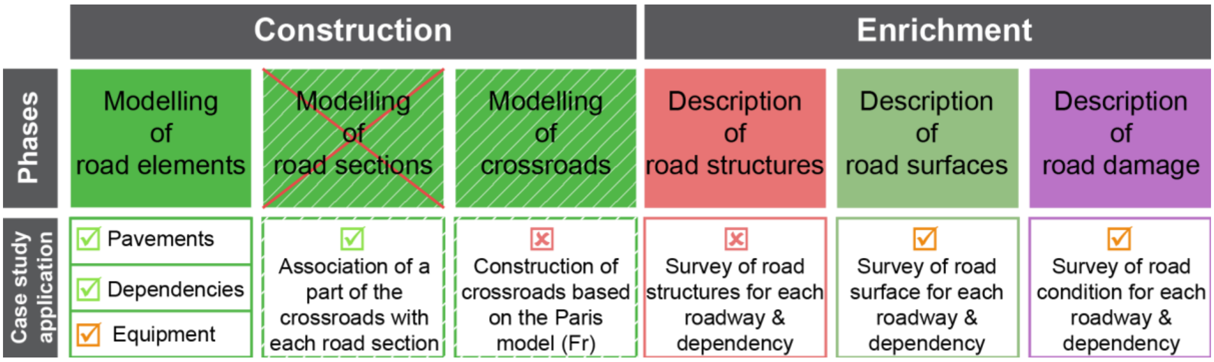

FIG. 5: Case study application (Pavard, 2023).

5.1 The construction of the spatial framework of Cachan's roads: road rights-of-way

5.1.1 Constructed data

The road elements are modelled by photo-interpretation of high resolution aerial images. Corrections are made by field surveys for areas that are not identifiable from the images, such as those covered by vegetation or building shadows. An automated construction process has been proposed for these data, based on geographic data produced at the national level (Pavard et al., 2021; Pavard et al., 2018). Road sections are then modelled by splitting crossroads into as many sections as there are roads that terminate at them, with each portion assigned to a road section. The process is automated and also makes it possible to match surface objects of the framework with linear objects of other road frameworks (Fig. 4a, p.7), making them interoperable (Pavard et al., 2022). The produced database distinguishes road features at different levels, from the most general, where roadways and dependencies can be identified, to the finest, where the types of roadway (main, bus, etc.) and facilities (pavements, parking, etc.) are identifiable (Fig. 12).

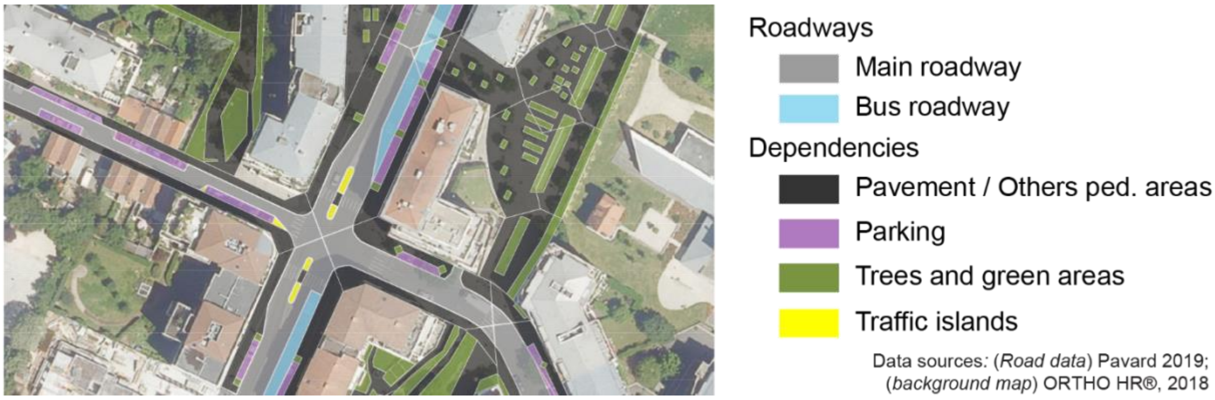

FIG. 6: Example of road data for Cachan (adapted from Pavard, 2020).

5.1.2 Data use cases

The spatial framework provides essential information for road managers. Firstly, they need to know the area of their roads in surface units instead of just linear units, as the surface unit is used for billing maintenance work (George et al.,2019). For instance, Cachan's roads cover 78 km in length and 0.9 km² in area. Secondly, it is crucial for road managers to be able to differentiate between roadways and dependencies to better understand the road assets and plan their management. In Cachan, roadways cover 438,300 m² while pavements cover 191,150 m².

Other relevant information includes ownership (administrative classes), road type, and traffic, which can be obtained through interoperability of the spatial surface framework with road graphs. These data help in constructing other useful knowledge for road management (see Fig. 1 p.4) and in designing the road (see Fig. 10, p.13). For example, Cachan’s roads have four administrative classes: “motorways”, “departmental roads”, “communal roads”, “other roads in the private domain”. The data indicate that motorways cover an area of 15,860 m² while communal roads cover 539,300 m².

5.2 The enrichment of the spatial framework of Cachan's roads: surface and damage

5.2.1 Data enrichment

The spatial framework is enriched by information on road surfaces and damage. To achieve this, a field survey process is used, which involves manual surveys using geotagged photographs taken on site (Pavard et al, 2019). The analysis of these images is used to populate attributes describing the surface materials, such as their description, modularity, or damage (see Fig. 10, p. 13). Additionally, the images are linked to the spatial framework using the geographical coordinates recorded at the time of shooting. These data enable the identification of the surface material of each road element and the calculation of the right-of-way surfaces by material. They also provide information on the general condition of each road element by road section (Fig. 13).

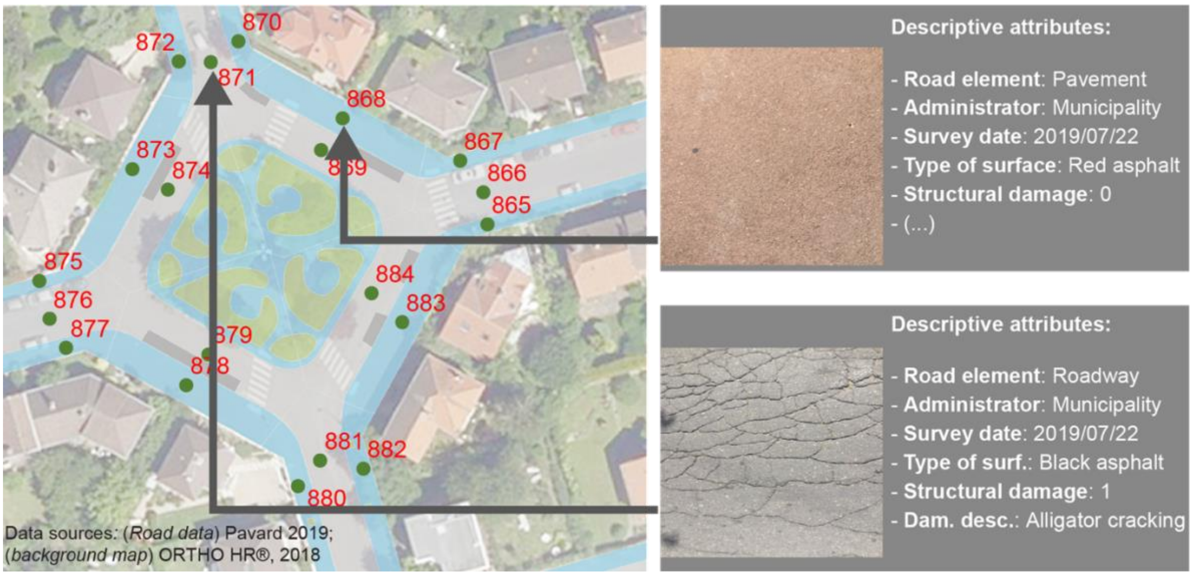

FIG. 7: Example of data enrichment for Cachan (adapted from Pavard, 2020).

5.2.2 Data use cases

The enriched framework allows for more specific business questions related to the technical management of the infrastructure. Firstly, it enables the identification of the surface materials used for each road element and their distribution on the territory (Fig. 14). Secondly, it allows the road manager to establish strategies for maintenance operations. At the project level, the road manager can quantify the maintenance operations and make appropriate choices based on the material environment. At the territory scale, the road manager can schedule maintenance over time based on costs and material supply.

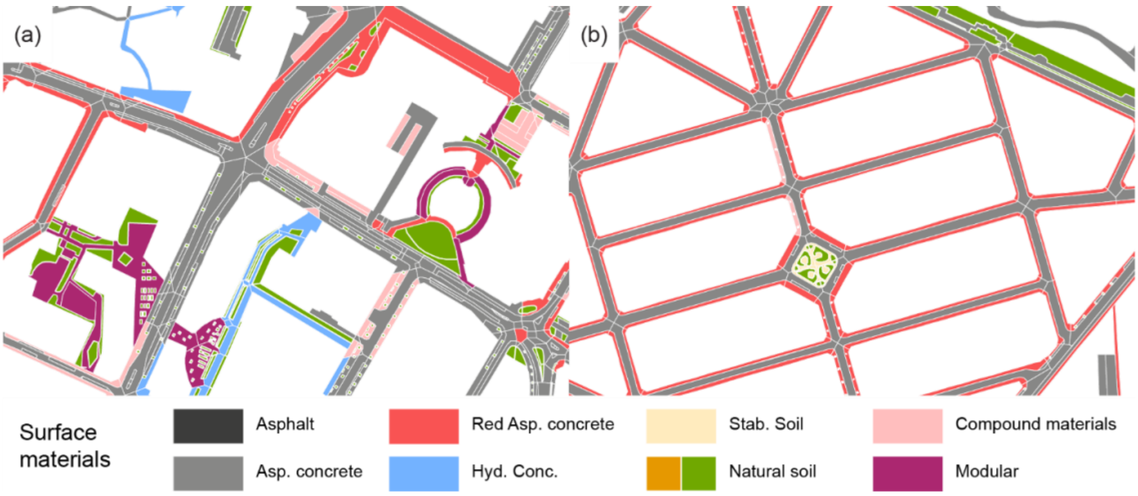

FIG. 8: Data enrichment by surface road for Cachan (adapted from Pavard, 2020).

Cachan's roads can be characterised by their paving materials and level of damage. For paving materials, bituminous and asphalt concrete represent 80%, with 90% being "black" materials and 10% being "red" materials. The addition of iron oxides to obtain the red colour increases the price of the material, making it essential to know its use over the territory. Materials with hydraulic binder represent 2.5%; they are mainly used for pedestrian spaces in the city centre. The finishes used enhance the spaces and give them a more natural appearance. Asphalt represents 0.4% and is mainly used on pavements. Natural soils cover 10% of roads and are used for roadway appurtenances in residential areas or for amenity spaces in the city centre. Modular materials such as pavers, bricks, or slabs cover the remainder of the road. Concerning damage, fatigue cracks cover more than half of the road elements, and they are the most prevalent type of damage among the structural damage. Material scuffings are the most prevalent type of surface damage (about 15%). This localised information helps the road manager to plan maintenance operations by prioritising the most damaged sections and road elements.

Beyond these characterisations, the framework allows for a more comprehensive approach to managing the road infrastructure in its environment. It enables the analysis of the co-existence between damage and other elements and other environmental factors, such as vegetation or technical networks. This analysis provides insights into the causes of damage and helps to facilitate the implementation of preventive maintenance strategies. In Cachan, the analysis was conducted by cross-referencing data from three technical networks (sewerage, electricity, and gas). On-site inspections highlighted a potential relationship between damage and the presence of technical networks: ruts, subsidence, transverse, longitudinal, or alligator cracks appeared to be partially correlated with the presence of a network, and cross-analysis confirmed these correlations. For instance, the results reveal that when a road element supports a buried utility network, it is twice as likely to experience deformation, cracking, or pulling (Fig. 15b).

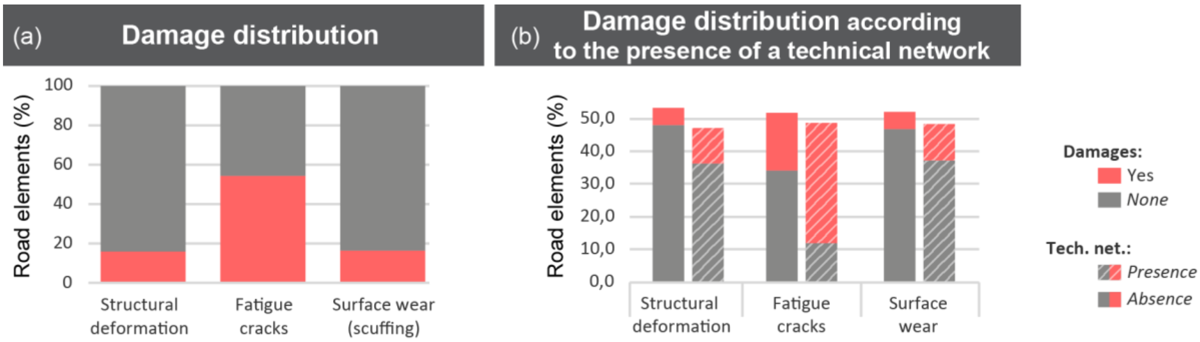

FIG. 15: Data enrichment by road damage for Cachan (adapted from Pavard, 2020).

5.3 Discussion of the application on Cachan

Regarding feasibility, several obstacles have been identified:

- Firstly, the implementation of such a spatial framework is dependent on the financial, technical, and human resources available to the local authority. To enable less developed municipalities to produce their spatial road framework, simple solutions have been developed.
- Secondly, technical information is not always available in a suitable format or is simply unknown. In some cases, such as completing information on roadways, simple processes can be applied; in others, such as road structures, the information is less accessible. In such cases, new technologies and methods can provide solutions. For example, drone imagery can be carried out during maintenance operations and the images can be classified using artificial intelligence algorithms (Lu et al., 2022; Davis et al., 2021).

Regarding the benefits of the framework, several business applications have been identified:

- **Global issues** – how the road system is organised within a given area, the distribution of its various components, and the space occupied by the road and its components
- **Material issues** – what the surface materials are, how they are distributed over the area, and what their significance is in terms of use
- **Damage issues** – what the road condition is and which sections require maintenance
- **Planning issues** – how maintenance operations within the area can be planned, how the medium- and long-term maintenance of the road can be budgeted based on its condition and materials.

GISs represent a powerful tool that can be used as a foundation for managing large infrastructure, such as roads. However, such systems are less effective when it comes to implementing localised strategies, such as local maintenance management. This type of management requires more detailed models, such as those proposed by BIM. Currently, BIM deployment projects for infrastructure are underway (Biancardo et al., 2020a; Biancardo et al., 2020b) and this is referred to as BIM infrastructure or I-BIM (Vigniali et al., 2020). A municipality responsible for managing roads requires both levels of modelling to establish the suitable management of its infrastructure at both the territorial and site level (D'Amico et al., 2020). To be effective, these two levels of modelling need to be connected through processes of data exchange, user interfaces, and so on (Sani and Abdul Rahman, 2018; Karan, 2016).

6. CONCLUSION

The urban road is a crucial part of the infrastructure in an urban environment. Due to its various uses, many stakeholders are involved in its maintenance. The range of interventions carried out can affect its overall performance, which raises questions about infrastructure management and optimisation. Until now, technical and scientific studies have approached this issue from two main perspectives: firstly, management is considered from the perspective of the road environment, particularly technical networks (Bouttier et al. 2013; Cerema 2005); secondly, when the road is at the centre of the process, it often only takes into account one dimension, namely the technical dimension, and neglects its geographical dimension, for example (Christory 2015; Debreu 2013).

This article has aimed to contribute the design of a spatial road framework in a GIS. This is part of a constructability vision aimed at providing reasonable assurance of achieving the objectives of any construction project over its life cycle (Gobin 2010). The proposed spatial framework takes into account both the geographical dimensions (urban engineering) and the technical dimensions (civil engineering) of the infrastructure. To ensure its usefulness to as many stakeholders as possible, it was developed using an accompanying modelling process. This process enabled the results of different modelling phases to be compared with the knowledge and requirements of the stakeholders of the modelled object, thus enabling informed decisions to be made.

The process is designed in two phases. The first one concerns the construction of a spatial framework to model and represent the geographical dimensions of the road, and the second one concerns the enrichment of the framework to analyse and describe the contextual and technical information to be integrated. The entire process was applied to a French case study, specifically the town of Cachan in the Paris metropolitan area, encompassing various potential urban developments. This application served to validate the feasibility of the process and subsequently emphasize the advantages of implementing a spatial framework for effective the road infrastructure's environment management.

Beyond that, this research forms part of a reflexive approach that questions the usage of modelling tools for road infrastructure management. The current trend in this field is the development and standardisation of BIM for infrastructure, primarily driven by specialists in architecture and civil engineering who have recognized the benefits of using these tools in managing building projects. Consequently, numerous government transport bodies are now crafting roadmaps for the implementation of infrastructure BIM (Ghasemzadeh et al., 2022; Borrmann et al., 2021). However, this BIM-centric approach proves sufficient for managing buildings but falls short when it comes to linear infrastructures (Garramone et al., 2020). This holds particularly true for urban road infrastructures, which are interconnected with and affected by numerous other infrastructures. Spatial referencing and the tools provided by GIS enable the analysis of these interactions and facilitate infrastructure management planning. Road managers who have turned to BIM acknowledge these limitations and are seeking to integrate their road BIM models with GIS. This integration can be achieved either through the use of connectors developed by major BIM and GIS companies (GEOBIMs) or by converting BIM models into GIS models. However, in the former case, the BIM model's structure prevents the full utilization of GIS analysis tools, while in the latter case, there is a substantial loss of information during the conversion process from BIM to GIS models. From our perspective, these two approaches are limited as they primarily address the needs and constraints of BIM modelling without adequately considering the requirements and limitations of GIS modelling. The spatial road repository presented in this article offers a potential avenue to standardize road GIS models and, consequently, establish the groundwork for the integration of BIM and GIS in the context of road infrastructures.

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