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Creating a Digital Twin of the VCI highway from inductive-loop data

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Dissertation Planning

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Resumo

O excesso de veículos nas grandes cidades é uma questão que se tem agravado nas últimas décadas, devido à elevada concentração de pessoas no espaço urbano. Este aumento provoca frequentemente o congestionamento nas redes rodoviárias, o que constitui ainda hoje um dos principais desafios dos Sistemas de Transporte Inteligentes (ITS), verificando-se sobretudo nas grandes áreas metropolitanas. Para além de prejudicar a atividade económica nas cidades, o congestionamento do tráfego afeta, principalmente, a saúde, em resultado da poluição, provocando, ainda, um elevado número de acidentes. A Via de Cintura Interna (VCI), uma via rápida no Porto, Portugal, apresenta estes problemas.

Embora ainda em regime experimental, a modernização dos sistemas de controlo de tráfego, na área dos ITS, tem trazido soluções inovadoras para a resolução destes problemas. De entre elas, destaca-se a aplicação de Digital Twins para as redes rodoviárias. Esta nova tecnologia beneficia a gestão, planeamento e monitorização do trânsito através de uma versão digital das redes rodoviárias atualizadas em tempo real, contribuindo para a melhoria da tomada de decisões na sua coordenação.

Com este trabalho, pretende-se complementar a plataforma *Next*, desenvolvida pela empresa ARMIS, destinada a monitorizar as redes urbanas através do controlo inteligente de tráfego. Mais precisamente, pretende-se a criação de um *digital twin* da VCI num simulador microscópico (*SUMO*).

De modo a ultrapassar algumas barreiras relacionadas com a cobertura limitada dos detetores fixos na rede, serão utilizadas técnicas de *Machine Learning* para gerar dados sintéticos em regiões desprovidas de sensores. Esta dissertação foca-se, assim, na análise de técnicas de replicação digital do tráfego, baseadas em mineração de dados (abordagem *data-driven*) e simulação (abordagem *model-driven*), com aplicação em sistemas deste âmbito.

Este estudo visa a utilização prática em ambiente de mobilidade automóvel, sendo que as técnicas desenvolvidas serão integradas nas aplicações de gestão de tráfego em desenvolvimento numa colaboração entre o LIACC-FEUP e a empresa ARMIS. A validação dos algoritmos explorados será realizada através do uso de dados reais de circulação automóvel no Porto, fornecidos pela empresa acima referida. Estes serão provenientes de detetores de laço indutivo (ILDs), colocados sob o pavimento da VCI.

Em suma, este projeto contribuirá para o domínio da gestão do tráfego, procurando aperfeiçoar as aplicações desta área com a finalidade de promover uma maior fluidez do mesmo.

Abstract

The excess of vehicles in big cities is an issue that has worsened in recent decades due to the high concentration of people in urban spaces. This increase often causes congestion on road networks, which is still one of the main challenges of Intelligent Transport Systems (ITS), particularly in large metropolitan areas. In addition to harming economic activity in cities, traffic congestion mainly affects health due to pollution and causes a high number of accidents. The Via de Cintura Interna (VCI), a highway in Porto, Portugal, has these problems.

Although still experimental, the modernisation of traffic control systems in ITS has brought innovative solutions to solve these problems. Among them, the application of Digital Twins for road networks stands out. This new technology benefits the management, planning and monitoring of traffic through a digital version of the road networks updated in real-time, improving decision-making in their coordination.

This work aims to complement the *Next* platform, developed by the company ARMIS, designed to monitor urban networks through intelligent traffic control. More precisely, the intention is to create a *digital twin* of the VCI in a microscopic simulator (*SUMO*).

This work will employ *Machine Learning* techniques to generate synthetic data in regions devoid of sensors to overcome some barriers related to the network's limited coverage of fixed detectors. Therefore, this dissertation focuses on analysing digital traffic replication techniques based on data mining (*data-driven* approach) and simulation (*model-driven* approach), with application in systems of this scope.

This study aims at practical use in an automobile mobility environment since the techniques developed will be integrated into traffic management applications under development in collaboration between LIACC-FEUP and the company ARMIS. The explored algorithms will be validated through real data on vehicle circulation in Porto provided by the company mentioned above. These will come from inductive loop detectors (ILDs) placed under the floor of the VCI.

In short, this project will contribute to the field of traffic management, seeking to improve the applications in this area to promote greater fluidity.

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Abbreviations and Symbols

DT	Digital Twin
ITS	Intelligent Transport Systems
VCI	Via de Cintura Interna
ILD	Inductive Loop Detector
FD	Fundamental Diagram
MFD	Macroscopic Fundamental Diagram
NMFD	Normalized Macroscopic Fundamental Diagram
IMED	IMage Euclidean Distance
SUMO	Simulation of Urban MObility
AS	Actual System
CPS	Cyber-Physical System
AVI	Automated Vehicle Identification
AI	Artificial Intelligence
ML	Machine Learning
DL	Deep Learning
IoT	Internet of Things
PLM	Product Lifecycle Management

Chapter 1

Introduction

This first chapter provides an overview of the project's context, motivation, and goals, as well as the document's structure. It aims to provide a clear and comprehensive understanding of the project's purpose and to set the stage for the rest of the document.

The Context section clarifies the context in which this research happens and how it builds on existing work in the field.

The Motivation section explains the need for the project and the motivation behind it. It identifies the problem this project seeks to solve and provides a compelling argument for why it is relevant, addressing its contributions to the area.

The Goals section outlines the project's goals by presenting a clear and simple summary of its specific objectives.

Finally, the Document Structure section delineates the document's structure, including a summary of the contents of the subsequent chapters. It intends to assist the reader in better understanding the document's organisation and navigating its contents more effectively.

1.1 Context

In the last decades, the area of transport has been encountering issues, such as traffic congestion and accidents, which accompany the development of urban cities. For example, since the movement of people and goods between cities mainly depends on the road network, problems within the traffic system significantly impact practically all areas of economic activity. Moreover, one of the causes of the environmental crisis is the use of fossil fuels by conventional automobiles with internal combustion engines, which release gases like carbon dioxide and hydrocarbons. In addition to the damage to the physical health of citizens resulting from pollution, the stress travellers accumulate during their trips also deteriorates their mental health. These are just a few examples of damage caused by traffic congestion, which has been getting worse over time.

All these problems stem from the inefficient management of transport flows. As the city population grows, the vehicle-to-population ratio grows accordingly, exacerbating the situation. As transportation difficulties rise, modernising and digitising transportation through intelligent technologies becomes a priority development area.

The need for modernisation led to the emergence of Intelligent Transport Systems (ITS). ITS refers to smart systems using innovative developments in modelling transport systems and regulating traffic flows. It provides end users with more excellent information content and safety, as well as qualitatively increasing the level of interaction between road users compared to conventional transport systems.

A new concept emerges to ensure the effectiveness of the ITS: the digital twin. A Digital Twin (DT) aims to reflect the performance of the real-world product by simulating a virtual space. It is a new concept, including creating a new virtual entity in cyberspace, imitating the original physical entities in most aspects, and monitoring, analysing, testing, and optimising it.

The Via de Cintura Interna (VCI) highway in Porto, Portugal, is an excellent example of all traffic problems. As it is a road that gives access to most of the urban arteries of Porto and Vila Nova de Gaia, there is a large influx of vehicles on this highway. It thus presents congestion problems, aggravated at peak hours due to people commuting from home to workplaces (primarily in city centres) and vice versa.

This work will be carried out in collaboration with ARMIS, a technological solutions company, more precisely with its ITS module. ARMIS developed the platform *Next*, intended for monitoring, managing and planning urban networks through intelligent traffic control, which applies the concept of artificial transport systems.

Hereupon, this dissertation intends to improve this platform by replicating traffic behaviour on Porto's networks more reliably, focusing on VCI.

1.2 Motivation

DT refers to a tool that combines all of the collected data and precisely recorded city signs to get new insights into urban traffic from several perspectives, such as road supply and demand. The knowledge gained allows for optimizing the road network structure through traffic simulation and enhancing overall traffic efficiency in the city. Additionally, integrating DT in intelligent transportation helps increase decision-making execution, safety, and vehicle stability, beyond expediting smart and safe driving.

This dissertation intends to complement the *Next* platform with a VCI Digital Twin. Integrating this new technology makes the system more reliable, reducing discrepancies between simulated and real values. Thus, the digital model of the VCI network will be closer to the actual behaviour of the traffic on this highway.

Analysis of the available literature indicates that this technology is still insufficiently studied. There is not enough information regarding existing models of ITS services in the literature, making it challenging to develop and implement specific models of transportation infrastructure together with appropriate information systems.

On the one hand, this study will benefit ARMIS, as it aims to improve its *Next* platform. On the other hand, it will be highly valuable for the ITS field and for spreading the notion of DTs in this industry, as this term is still in its infancy.

1.3 Goals

As discussed in the previous sections, ITS plays a pivotal role in maintaining traffic since it effectively addresses road congestion issues. Due to their potential, DTs constitute a significant area of interest in this field.

The primary objective of this dissertation is to develop a Digital Twin for the Via de Cintura Interna (VCI) highway in Porto, Portugal. The descriptive model will feed from data from inductive loop detectors belonging to its infrastructure.

Moreover, this document also aims to study data generation techniques in places devoid of sensors. If the produced information is accurate, it will significantly benefit the model and help to correct any flaws brought on by the detectors' restricted coverage.

In order to achieve the goals indicated above, this dissertation intends to fulfil the following specific objectives:

- Study of the theme's relevant topics and presentation of its state-of-the-art;
- Scrutiny and processing of data from sensors;
- Development of a VCI digital twin using the microscopic traffic simulator SUMO;
- Model validation through comparison with sensor data;
- Data generation in highway locations devoid of sensors;
- Incorporation of produced data in the digital twin and respective validation.

In addition to generating a solid dissertation document, the developed work must be valuable to ARMIS.

1.4 Document Structure

In addition to the Introduction, this dissertation contains three more chapters.

The second chapter, Literature Review, exhibits the state of the art of the topic under study, summarizing related articles. It is divided into central three sections. The first, Research Plan, establishes the methodology used to search for knowledge about the area in question. The second, Background, presents the main terms of the investigation. More precisely, it introduces the field in which this dissertation operates,the Intelligent Transport Systems, and talks about the various types of traffic Data Sources, focusing on the Inductive Loop Detectors, which this work further explores. Then, it introduces the Digital Twin concept, highlighting the advantages, enabling technologies and main challenges of this new technology. It also describes a general architecture for its construction, implementation phases, and primary applications. It ends by introducing the Fundamental Diagrams, which are essential elements for the representation and analysis of traffic. Lastly, the third section, Related Work, describes an approach for generating synthetic data in regions devoid of sensors. This dissertation intends to replicate this technique, along with others that arise. In the end, it is expected to have a conclusive comparison of the best techniques for this purpose.

The third chapter, Problem and Proposed Solution, seeks to concisely explain the problem in question, presenting a methodology for its resolution based on some work already carried out in this first semester. Section Problem Definition covers the precise definition of the problem, followed by the Methodology section about the methodology mentioned above. To finish, the section Work Plan details a work plan for this dissertation.

Finally, the last chapter, Conclusions and Future Work, provides an Overview of the document's themes and concludes the preparatory work for the dissertation developed in this first semester. The document ends with the SMART Analysis and SWOT Analysis of the project.

Chapter 2

Literature Review

2.1 Introduction

This chapter aims to provide an advanced and up-to-date picture of the state-of-the-art of this dissertation's theme. It is composed of three main sections.

The first section, Research Plan, describes the methodology for searching articles related to the theme.

The second, Background, is organized thematically, being divided into several subsections according to the main concepts that relate to the theme. More precisely, it introduces the area in which this study fits: Intelligent Transport Systems. It then summarizes the main types of traffic Data Sources, indicating the associated problems and advantages. An in-depth description of the sensors explored in this work, the Inductive Loop Detectors, follows. Next, it provides a comprehensive overview of the current knowledge on Digital Twin. Along with arguing a definition for this term, it presents their enabling technologies and some examples of their applications. This subsection ends with an exposition of a generalized architecture of this new technology and its main challenges. Finally, some essential diagrams for the field of traffic analysis are explained, which are called Fundamental Diagrams.

The third and last section, Related Work, focuses on studying solutions to the problem of limited sensor coverage. It includes an image-based approach, which this dissertation intends to replicate. In the end, it is expected to have a detailed comparison of several methods to solve this problem through the in-depth analysis of their results.

2.2 Research Plan

The methodology used for the literature review began by formulating four questions fundamental to understanding the topic of this dissertation:

1. What is a Digital Twin?
2. What is a Digital Twin of a traffic network?
3. How does one build and validate a digital twin of traffic networks?
4. How to derive Fundamental Diagrams of traffic based on data from inductive loop detectors?

A search was conducted for at least five articles to address each question. The search gave priority to the most recent and most relevant articles. Fortunately, this task was not difficult, as this topic is still in its infancy.

In total, 25 articles were analyzed. The following table presents a more detailed description of this analysis:

Table 2.1: Articles found in search

	Research questions				
Search Systems	**Q1**	**Q2**	**Q3**	**Q4**	**Total**
UPorto Research and Discovery Platform	5	1	4	1	11
Google Scholar	2	5	1	6	14
Total	7	6	5	7	25

The following chart (2.1) summarizes the publication dates of the articles:

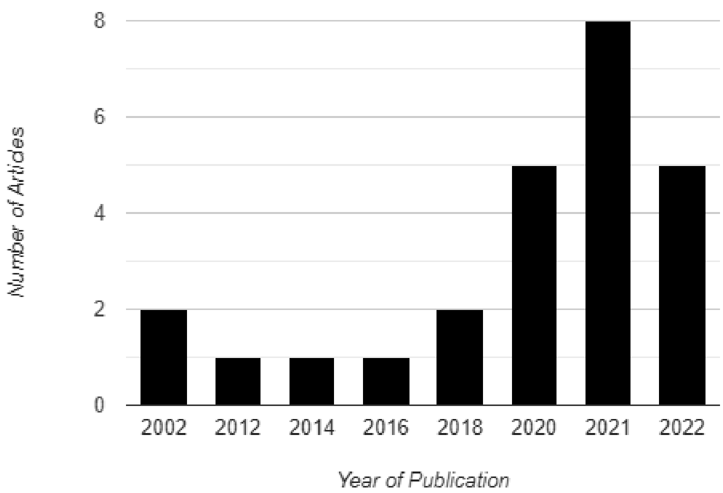


Figure 2.1: Year of publication of the articles found

The prevalence of more recent articles is easily noticeable. All the older ones are specific to Inductive Loop Detectors, which is reasonable given the longevity of these devices, introduced in the early 1960s. However, their relevance remains, as they allow a better understanding of these sensors.

The contents of these articles were filtered, with the essential ideas summarized in the following two sections.

2.3 Background

2.3.1 Intelligent Transport Systems

[8] categorised the main issues concerning transport systems' operation as objective or subjective:

Objective problems:

- increasing vehicle-to-population ratio;
- intensified use of individual transport;
- decreased efficiency of urban passenger transport;
- increased need for city residents to move;
- disproportion between the vehicle-to-population ratio and the pace of road construction;
- problems of urban planning and urban area development.

Subjective problems:

- imperfect system for organizing and managing the development of the road transport complex;
- insufficient legislative base at the local and regional level for managing the transport system of the city, region;
- insufficient information component when making management decisions;
- insufficient funding for the development of road networks and transport infrastructure;
- unresolved property issues and issues of delineation of property rights and management of transport infrastructure facilities;
- negative impact of the human factor.

The ITS includes all city services, including traffic police, ambulance, fire departments and other services [8]. In general, ITS helps in solving the following tasks:

- optimization of the distribution of traffic flows in the network in time and space;
- increasing the capacity of the existing transport network;
- providing travel priorities for a certain type of transport;
- transport management in the event of accidents, catastrophes or measures that affect the movement of transport;

- improving road safety, which leads to an increase in traffic capacity;
- reducing the negative environmental impact of transport;
- provision of information on the state of the road to all interested parties.

Intelligent transport systems have made it possible to successfully improve the transportation network and address its primary issues. The main obstacle to introducing ITS is the underdeveloped infrastructure. The presence of sensors, surveillance cameras, IoT and other infrastructure on the road transport network determines the possibility of implementing the system. The many components of smart cities must be intelligently regulated, utilizing data provided by physical assets. Thus, ITS can broadly be defined as the continuous and quick collection of information regarding traffic conditions on roadways using telematic equipment, encompassing the storage, processing, validation and analysis of measured data. It also enables short-term traffic forecasting (in the next 15 minutes or the following day) by utilizing real-time data from sensors, as intelligence in the transportation industry is quickly expanding. Machine Learning (ML) and Deep Learning (DL) techniques are employed to develop ITS due to the big volume of data produced by transportation systems.

These characteristics make these systems helpful in many applications, from traffic light regulation to delivering immediate replies to police in case of a traffic accident or other unexpected scenario.

Having defined what is meant by ITS, it is now necessary to specify its main components and participants:

- transport infrastructure;
- service and software infrastructure;
- vehicles;
- telematic equipment of transport infrastructure elements and vehicles;
- intelligent information boards, road signs and traffic lights with the ability to remotely control them;
- centers for collecting and processing information;
- decision making and traffic management centers.

[8] defines three main functions of ITS. The first consists of transport modelling through Digital Twins, a concept explored in the following subsection. The second is concerned with optimising the duration of traffic lights, aiming for the light signal scheme with the shortest transit time. Finally, the third is based on monitoring, planning and managing transport networks. This study focuses on the first function, comparing different ways of modelling road traffic.

A good illustration of the benefits of this technology at various levels is an ITS implementation in Chelyabinsk, Russia. [8]. This ITS can assist authorities in implementing legislation in addition to their practical duties of enhancing road conditions. Some countries require documentation of the projects to be developed on the roads, such as the Russian Federation (REF). It is practical to save all traffic management projects virtually so that the documents are promptly available by just hovering the mouse over the street on the digital map. This way, construction work and the inspection of all technological traffic control devices become easier. For example, since the position of all communications is already in the system, installing a traffic light does not need contacting all local authorities (gas service, administration of electrical networks, and communication providers). Aided by cutting-edge analytical tools, this system can display *heat maps* of a city that depict the concentration of people in various regions or the primary accident locations. Another feature is to show the townspeople's direct correspondence, which provides insight into the townspeople's origins and destinations. In a mathematical model of the city's transport and passenger flows, correspondences are created based on a set of factual data, making it possible to forecast potential scenarios for the development of urban transport infrastructure.

Transport control centres aim to ensure regular traffic on the road network. These centres used to tackle traffic management issues but now require upgrading through ITS. Among the main functions of these centres is the organization of an efficient traffic flow and the monitoring of road networks. They are also in charge of notifying participants about alternate routes and coordinating forces during emergencies. These processes provide control over eradicating the consequences of these scenarios on the road network. Every metropolis has a traffic control centre, where the operators are primarily responsible for making management decisions. The traffic management system comprises many systems for reporting traffic infractions, incident detection, vehicle counters and classifiers. The Transport Control Center receives all of this information in real-time, enabling it to get updates on the state and accessibility of urban transportation. Modernization of the centres is required, first and foremost, due to a rise in the information load on operators, which may result in an emergency scenario. A human working in such a facility is a potential source of errors since their response time is substantially slower than the system's. Furthermore, the volume of equipment monitoring data has risen due to the growth of sensor technology and computing technology, causing challenges in real-time status evaluation and prediction under traditional modelling conditions. The urge to automate operator tasks rises, leading to ITS implementation. Ideally, the entire system should operate autonomously without human involvement, with employees solely involved in system setup and monitoring. Therefore, with the advent of ITS, the functioning of transport control centres changed qualitatively: operators perform solely a controlling function and influence the adoption of strategic choices on transport network modernisation and development based on analytical projections. Experts in troubleshooting and setting up such a system have become fundamental.

2.3.2 Data Sources

The DT is a data-driven analytic system. It incorporates physical models and historical data to mimic real-world product performance in a virtual space. As such, it must perceive the current state of the physical entity by collecting the surrounding environmental information and communicating it in real time to the virtual model system. The essence of the concept raises the bar for precise detection and efficient transmission of various parameters.

When applied to highways, the central task is to model the real-world road system as accurately as possible throughout its life cycle while organically integrating roads with other components in the transportation system. This activity enables high-quality estimations of the system's performance during its lifespan. These unique properties make the collected data the most valuable asset of this technology, demanding a comprehensive review of the various methods for obtaining it.

The definition of the network state depends on the nature of the data source. [1] grouped available data into three broad types:

- **Static observations:** real-time information obtained in fixed locations in the network, e.g. from induction loops or surveillance systems;
- **Route observations:** usually obtained from GPS-enabled vehicles, smartphones or traffic operators;
- **Global observations:** usually obtained from a secondary source.

The first group frequently comprises metrics such as flow, density, volume, average velocity, occupancy or queue length at specific points in the network. It is one of the primary sources of real-time information. However, the main limitation of this type of data is the lack of intervisibility between locations with sensors.

The second group often includes metrics such as travel time, queue length and incidence of accidents at a certain point in the network. It entails vehicle-to-cloud communication, allowing the calculation of advisory speed using data gathered from vehicle sensors. Regarding GPS-enabled vehicles, taxis and buses are the most used probe vehicles. Furthermore, with the proliferation of smartphones, it is now simpler to collect information on location, incidents, travel times, and common routes followed by drivers.

Weather reports, special events (such as football matches), and other observations considered beneficial for prediction purposes, like the day of the week, exemplify data from the third group. By using data-driven approaches, it is possible to relate these external information sources, such as incidents and road works, to traffic conditions.

When incorporating this information into the system, its uncertainty may also require assessment, especially when using data from unreliable sources like smartphone usage. Traffic flow modelling uses the gathered data to deduce the features of transportation systems functioning, such as the degree, frequency, and length of congestion, traffic intensity, and loads at specific intervals. Some other metrics are also computed, including average speed and volume transportation of goods, passengers and the respective time cost.

One major obstacle to intelligent transportation is achieving precise information on the current transportation infrastructure. Data modelling and engineering construction are closely tied to the expertise of professionals in many sectors. Furthermore, the accumulated data is of poor quality and low value, making it hard to meet reality's urgent demand and the effect of the rapid application. Data sources are now the primary barrier to the advancement of DT technology, placing restrictions on data analysis and utilization.

Other challenges include the DT's security, particularly when data comes from IoT devices. There is a pressing need for approaches to increase the credibility of integrated simulation models and their predictions.

This section highlighted the importance of data in modelling traffic systems. Regardless of the traffic forecasting approach, historical data is just as influential as a source of real-time information. While data-driven approaches utilize the network's past to anticipate its evolution, model-driven methods use it to calibrate the parameters used in traffic modelling. Its enormous relevance, associated with the unresolved challenges mentioned above, make data the main bottleneck for developing DT technology.

It is important to emphasize that the work in this thesis will be based on static observations. More precisely, the data will originate from inductive loop detectors strategically placed across the VCI network.

2.3.3 Inductive Loop Detectors

Inductive loop detectors (ILDs) are devices commonly used in traffic control systems to detect the presence of vehicles. Typically, they are placed under the pavement of roads, detecting changes in a magnetic field brought on by a moving vehicle.

The magnetic field, created with a coil of wire, is disturbed when a vehicle drives over the loop, as the metal in the vehicle's undercarriage alters the current flowing through the coil.

By analyzing the changes in the current, it is possible to deduce numerous traffic metrics. In addition to generating traffic data, they enable the automation of a few procedures, such as activating traffic lights or controlling gate barriers.

- **Single-loop detectors:** the most basic sort of ILD used to detect the presence of a single vehicle;
- **Multi-loop detectors:** often utilized in multi-lane applications to detect the presence of multiple vehicles;
- **Dual-loop detectors:** frequently employed in one-way roadway applications to detect the presence of vehicles in both directions;
- **Smart loop detectors:** the most sophisticated ILDs available, capable of providing extensive information about the vehicle, such as its size, length, and class.

The first type of ILDs, single-loop detectors, is the most commonly used. Its popularity stems from its low costs, resulting from the device's long lifespan and minimal maintenance requirements. They can detect the presence of a vehicle with a high degree of accuracy, even in adverse weather circumstances. Through its utilization, three essential traffic parameters - speed, volume, and occupancy - can be inferred in real-time.

As previously stated, one of the main problems of ILDs is their limited network coverage. Despite this hindrance, these devices are still widely used for traffic data collection. The numerous advantages that come with them account for their widespread use. First, they are cost-effective since they use the existing loop infrastructure. It would be preferable to integrate with already-installed sensors, usually ILDs, instead of implementing new technologies while disregarding prior expenditures. Furthermore, this technology is nonintrusive and anonymous, unlike other systems that require a specific vehicle identity, like Automated Vehicle Identification (AVI). Additionally, modern sensor technology allows researchers to collect more precise and trustworthy traffic data, leading to more effective traffic monitoring and control. Thanks to their simplicity and robustness, these devices are relatively low cost, easy to install and maintain, and reliable and accurate.

A detector card is a circuit board customarily installed inside a loop detector, responsible for processing the signals generated by the inductive loop in the pavement. This component includes the electronics required to interpret the loop's signals and provide a detection output to the rest of the system.

Detector cards used with traditional ILDs are often bivalent, with the output being either 0 or 1, depending on vehicle presence. However, detector card technology has advanced to the point where it is now possible to obtain the inductance change across the loop from the vehicle's passage. The rapid scan rate of the detector allows for varied levels of inductance change, which produces a waveform, often known as a vehicle signature.

Vehicle signatures vary depending on vehicle speed and type and display various characteristics. Many features may be derived by exploiting those vehicle signatures directly or indirectly.

[7] argues that there are two broad categories of feature vectors in this context: vehicle-specific and traffic-specific. The vehicle-feature vectors are mainly dependent on the vehicle type. Vehicle length is an example of this category. Under the same sensor, installation settings, and driver behaviour, these features should remain invariant. Traffic-specific features like speed and occupancy highly relate to traffic conditions. Another example of these features is the skew rate, representing the slope value at point 0.5 of the normalised signature.

2.3.4 Digital Twin

As the transportation sector has evolved, the smart city network systems have become an inevitable trend of upgrading and evolution in the future generation road system technological form. Digital Twins (DTs) arise as a vital instrument for these systems, simplifying their management, analysis, and operation.

This section attempts to answer the following research questions:

- What is a Digital Twin, and what are some of its misconceptions with current and previous definitions?
- What are the enabling technologies associated with this technology?
- What are its main applications?
- What is the status of open research, and what are the challenges of Digital Twins?
- Where and when should a Digital Twin be developed?
- Why should a Digital Twin be used?
- How to design and implement a Digital Twin?

2.3.4.1 Term Definitions

Formal ideas about Digital Twins have existed since the turn of the century. The term "twins" usage dates back to National Aeronautical Space Administration (NASA)'s Apollo program when two identical space vehicles were created to allow mirroring of the space vehicle's circumstances during the voyage. In 2012, NASA published a study titled "The Digital Twin Paradigm for Future NASA and US Air Force Vehicles," establishing a crucial milestone in defining Digital Twins. The stated description is as follows:

> "A Digital Twin is an integrated multiphysics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin." [4, chap. The Digital Twin (Concept)]

This definition is far too specific for NASA's interplanetary vehicle development. The meaning of this term has varied over time to reflect new applications.

Due to the ever-changing definitions, there is a degree of uncertainty around the terminology, making it challenging to describe. On top of that, differentiating DTs from generic computer models and simulations has not been made easier by academia or industry. For instance, some claim that a digital twin is a virtual representation or model that interacts with the physical system throughout its life cycle. Other commonly utilized definitions emphasize the necessity of information exchange between the two spaces, encompassing sensors, data, and models. Some people view a digital twin as the cyber component of a cyber-physical system (CPS). The promising future of this technology requires a more definitive definition.

[9] conducts an exhaustive systematic literature review on Digital Twins, seeking to narrow down the meaning of this concept. The authors list the ability of simulation along the product life cycle, the synchronization of the cyber system with the physical assets, the integration of real-time data, the behavioural modelling of the physical space and the services provided by the virtual system as the main aspects that characterize the digital twin definition. In light of those above, they define the word as follows:

> "A set of adaptive models that emulate the behaviour of a physical system in a virtual system getting real-time data to update itself along its life cycle. The digital twin replicates the physical system to predict failures and opportunities for change, prescribe real-time actions for optimizing and/or mitigating unexpected events by observing and evaluating the operating profile system."

The uncertainties about this term result in some misconceptions by some authors. Amongst these is the idea that DTs must be an exact 3D model of physical objects. On the other hand, some people mistakenly believe that a Digital Twin is simply a 3D model. [3] presents three definitions that help identify the general misconceptions in the literature:

- **Digital Model:** a digital version of an existing or planned physical thing, with no automatic data flow between them. Examples of digital models are plans for construction, product designs, and development. The key distinguishing characteristic is no automated data interchange between the physical system and the digital model. In other words, after the production of the digital model, any modification to the actual object has no bearing on the digital model;
- **Digital Shadow:** a digital representation of an object with a one-way flow between the physical and digital object. A change in the physical item's state impacts the digital version, not the other way around;
- **Digital Twin:** a system where data is transferred seamlessly back and forth between an existing physical entity and a digital object. Any modification to the physical thing causes an automatic adjustment of the digital entity and vice versa.

In summary, it has been shown from this review that this concept is a somewhat nebulous term. According to certain writers, like [9] and [2], the fundamental idea behind a Digital Twin is a high-fidelity virtual model of a physical entity with the capacity to replicate and simulate the states and behaviours of the latter throughout its lifespan. These do not require a bidirectional automatic information exchange. Others, such as [3] and [5], go a step further and say that it is best described as the automated data integration between a physical and virtual machine in either direction. The virtual model is updated using information gathered from the physical environment. While operating in real-time, the physical twin enhances its performance by exploiting the knowledge learned from the data.

2.3.4.2 Enabling Technologies

The task of modelling reality in a digital twin must consider sensors, multifunctional models, data from many sources, services, and other factors. This process is quite complex as it needs a large amount of data. This new tool thus becomes dependent on the evolution of some enabling technologies. The literature focuses mainly on three of them: IoT, Data Analytics and Simulation.

The Internet of Things (IoT) is the term for devices connected to the internet. It is about providing them with a sense of intelligence and the ability to collect information about their surroundings. The idea of interconnected devices enables developers to track and monitor everything we do, thus leading to a brighter world.

A DT must capture the pertinent elements, such as the necessary characteristics and relationships, of the actual system (AS) regarding its operations' contexts and environments. This process includes data collection, storage, calculation, and inference. IoT has increased the volume of data usable in manufacturing, healthcare, and smart city environments, thus enriching the accuracy of the virtual replication of the physical system.

Data analytics is an umbrella term that groups analytical concepts, as seen throughout the literature. Aside from methods for obtaining statistics from data, Artificial Intelligence (AI) and its subsections, especially Machine Learning (ML) and Deep Learning (DL), stand out. The broad definition of AI dates back to the late 1950s with the concept of creating "intelligent systems". Its subsection, ML, is the creation of algorithms that allow the computer to learn and act for the user without being explicitly programmed. It enables the development of software applications that autonomously gather and analyse data using complex algorithms. DL algorithms learn unstructured and unlabelled data using complex neural networks with autonomous input feature extraction instead of manual extraction. These networks employ machine learning to create deep learning models that can take longer to train because of the considerably more extensive neural networks but result in higher accuracy.

By building a linked physical and virtual twin, DTs can address the issue of seamless IoT and data analytics integration. Combining this technology with artificial intelligence approaches like ML and DL makes it possible to extract valuable information from the collected data about the environment. In addition to real-time data collection, this combination provides very effective services to the service provider and the end user.

Furthermore, DTs can utilise simulation to help with decision-making for maintenance or enhancement of the AS based on new needs and/or resource availability. Not only for a general device but also monitoring whole systems, simulation serves as the foundation for design decisions, validation, and testing. On the one hand, a DT's environment is designed to allow it to imitate the AS's behaviour to simulate how the system reacts. These simulation capabilities may be considered a "static feature" of the DT. Emulation, on the other hand, describes a DT's ability to sync with the AS to perform approximately like it. As a result, this aspect of DT might be referred to as a "dynamic feature".

Sensors and actuators are essential components in CPS, whereas models and data are critical components in DT. Technological advancements in these three domains have become crucial criteria for the promotion of DTs.

2.3.4.3 Implementation Phases

DTs can be built for various purposes, including non-digital system design, development, analysis, simulation, and operation to understand, monitor, and/or optimise the AS. This technology is widely used in many areas to understand better, regulate, and optimise the behaviour of complex systems, either at design time (for example, design-space exploration) or runtime (to increase performance/productivity or prevent failures).

The digital twin finds applications throughout the entire product life cycle management (PLM), which splits into three phases: design, production, and service. In the design phase, the DT is intended to develop the digital product design before actual execution. During this phase, the digital twin may be used for conceptual design, detailed design, and virtual verification of a product. In the conceptual design stage, the DT assists designers in formulating functional requirements. Using real-time transmission data can improve the transparency and speed of communication between clients and designers. In the detailed design stage, the DT enables simulation testing throughout the thorough design process to ensure the prototype can deliver the expected performance. Lastly, the digital twin enables simulation and predicts the performance of the physical products based on virtual models during the virtual verification stage.

Regarding the production phase, DTs strive for real-time monitoring and optimization, as well as anticipating the future condition of the physical twin, preventing downtime and malfunctions. It aids in determining the best combination of parameters and activities to maximize performance and offer projections for long-term planning.

Finally, the service phase relates to the steps after the sale/deployment, including product utilization and maintenance. In this phase, DTs can provide value-added services support for prognostics and health management (PHM). The PHM is an engineering process for preventing failures and predicting reliability and remaining useful lifetime (RUL). The DT, in this case, is created to increase the precision and efficiency of a product's life cycle monitoring.

Currently, relatively few digital twin applications support the entire product life cycle.

2.3.4.4 General Architecture

As summarised by [9], a DT architecture consists of several components and technologies categorically organized into three main layers: the physical layer, the network layer and the computing layer.

The first consists of physical entities identified based on the stage of the product life cycle. The network layer bridges the physical and virtual domains. It exchanges data and information. The computing layer involves the virtual entities emulating the corresponding real entities, including data-driven models and analytics, physic-based models, services, and users.

Each layer comprises some DT components (for example, hardware or software technologies, models, and information structures) that share similarities in their scope of use and interactions, having complementary functionalities.

The physical layer components carry real-time data for synchronizing the virtual twin with its matching physical twin, promoting anomaly detection, prediction, prescription, and optimization capabilities. The network layer involves connections and interactions between physical and virtual entities. This layer links all components so that they may share data and information with other components. The Service Oriented Architecture (SOA) method is DT's most commonly utilized middleware architecture. Its principles allow decomposing of complex and monolithic systems into applications consisting of an ecosystem of elementary and well-defined components. The computing layer is indispensable for the computation and decision-making of digital twins. It can be decomposed as an interconnected set of layers, including the following components: data, models, and modelling features.

2.3.4.5 Main Applications

The numerous applications of this new technology reflect its innovative character and potential. Currently, smart cities and manufacturing are the key research areas, with some healthcare-related uses of Digital Twin technology discovered. Other sporadic cases of applications include Maritime Shipping and Aerospace. Due to the fast advancements in connections made possible by the IoT, DTs are becoming increasingly popular. They have the potential to be extremely useful in smart cities. The capacity of smart city services and infrastructures to have sensors and be monitored using IoT devices is precious. As smart cities expand, connectivity and valuable data increase, and DTs become increasingly practical.

The DT is typically applied in contexts characterized by uncertainty and complexity, where working circumstances might change based on external and internal factors. This owes to its emulation capability, which allows it to adjust its original configuration and adapt to the present circumstances, known through its synchronous connection with the AS.

2.3.4.6 Primary Challenges

It is becoming clear that Digital Twin coexists alongside AI and IoT technology, resulting in shared challenges.

The present IT infrastructure is the first obstacle. The infrastructure must be suitable for the DT to succeed with IoT and data analytics. Without a connected and well-planned IT infrastructure, this technology won't be able to properly accomplish its intended aims.

The next challenge revolves around the data required for a DT. It needs to be high-quality noise-free data from a continuous, uninterrupted stream. The DT may underperform if the data is absent, poor, or inconsistent. Planning and analysis of device usage are required to determine the appropriate data be gathered and used for the effective deployment of a Digital Twin.

The privacy and security issues with DTs present a barrier in an industrial context, constituting the third challenge. There is a considerable risk of disclosing sensitive data due to the enormous volume of data they use. To overcome this obstacle, the primary enabling technologies for DTs must adhere to the most recent security and privacy conventions. Security and privacy cogitation for DTs data help to address trust difficulties with Digital Twins.

Trust difficulties establish another challenge from both the perspective of the organisation and the user. A DT's technology has to be further addressed and described at a basic level to ensure that end users and businesses comprehend the advantages of a DT. A better understanding helps overcome the barrier of trust. Another method to achieve this is model validation: ensuring that DTs work as intended. Additionally, as mentioned in the last paragraph, enabling technologies will shed more light on the procedures used to maintain security and privacy standards throughout the development, promoting user confidence.

The fifth challenge is related to the high expectations of this tool, as potential consumers only see the benefits and feel it will immediately save them time and money. The area is still in its infancy, which must be kept in mind while deciding whether to apply it. Caution is required to underline the obstacles that exist for DT expectations and the need for greater awareness. Strong IoT infrastructure foundations and a better knowledge of the data needed for analytics are essential for organisations to use DTs. Combating the notion that this technology should be employed just because of the prevailing trends is equally tricky. The benefits and drawbacks of its expectations must be explored to take proper action while setting up Digital Twin systems.

Despite DT's difficulties with IoT and data analytics, there are also particular challenges related to its modelling and development.

The absence of a standardised modelling methodology is an example of these challenges. Whether physics-based or designed-based, there has to be a traditional approach from the original design to the DT simulation. Standardised methodologies promote domain and user comprehension while facilitating information flow throughout Digital Twin development and deployment stages.

Another problem stemming from the necessity for standardised use is ensuring that information relating to domain use is conveyed to each development and functional level of Digital Twin modelling. This process guarantees interoperability with fields like IoT and data analytics, enabling Digital Twin's practical use in the future. Domain knowledge is crucial in the future creation of DTs and when leveraging IoT and data analytics.

2.3.5 Fundamental Diagrams

Fundamental diagrams (FDs) depict the relationships between several variables in a transportation system, such as traffic flow, density, and average speed. They are used to analyse traffic behaviour and to understand the interactions between various factors in a traffic system.

Typically, they illustrate how a road network's traffic flow (vehicles per unit of time) and traffic density (vehicles per unit length) relate to one another. This relationship is commonly known as the "fundamental relationship" or the "fundamental diagram of traffic flow." The FD describes how traffic flow and density change due to numerous factors such as traffic incidents, road network architecture, and traffic management strategies.

FDs come in various forms, such as capacity diagrams, which show the maximum flow a road network can accommodate under ideal circumstances, and jam diagrams, which show the relation between flow and density under congested conditions. These diagrams are crucial for comprehending traffic behaviour and making sensible transportation management and planning decisions.

Macroscopic Fundamental Diagrams (MFDs) illustrate the relationships between traffic variables at a broader scale, such as the level of an entire road network or a metropolitan region, as opposed to Microscopic Fundamental Diagrams, which do so at a finer scale. They are used to study traffic behaviour at the macroscopic level, particularly to assess the effects of large-scale events, like introducing a new transportation system or building a new road system, on traffic flow and density.

2.4 Related Work

The collection of flow and velocity at a single probe station allows easy estimation of FDs in simple linear streets. Nonetheless, no theory exists for calculating the FD in an extensive traffic network when the number of sensor stations is scarce (much less than the number of roads requiring FDs).

Alternatives include interpolating the FD from measurements to roadways without sensors or averaging the density/flow ratio in particular network areas. The latter leads to the so-called MFD, which relates an entire network's density, speed, and space-mean flow. In some cases, fusing data from different sources is also possible, making such procedures statistically effective.

The Aggregated Traffic Relationship (ATR) is a relationship between average traffic variables (like speed, density, occupancy or flow) for a specific network that does not necessarily have a well-defined shape that can be called an MFD. For instance, networks with an uneven and irregular distribution of congestion may display traffic states that are considerably below the top bound of an ATR and far too dispersed to reside along an MFD. Recent research has shown that as the transportation system gets crowded, the MFD shape of a heterogeneous network comprises several scatter points, which introduces uncertainty and imprecision into the traffic state estimation.

Most experimental studies published in the literature estimated the MFD using data from fixed sensors, such as ILDs, which might lead to biased estimates in urban networks. Recent literature proposes employing trajectory data obtained from probe vehicles to overcome this limitation. Few works have discussed the limitations of real data sets and their impact on MFD estimation, thus increasing the value of this dissertation.

[6] presents a method for estimating a "normalized" MFD to compute specific FDs in places where loop sensor data is unavailable.

The authors opted to represent the information as two-dimensional signals (images) to preserve it. Therefore, they built their estimation method on image analysis, retaining data integrity until the last phases (instead of first matching curves that induce a first approximation). Then they merge and scale main features using image classification and filtering tools. Lastly, obtaining a representation of the specific road where sensors are missing is feasible through its likelihood with other links within the same network.

According to the authors, the ultimate goal is a universal recipe to estimate FD suitable for all types of networks. However, recognizing that networks are complex structures described by many variables, we shall be satisfied with an approximation that employs as few of these variables as possible, a proper parameterization and a description of heterogeneity that yields reasonable estimates for most practical applications.

Thus, the central idea pursued by the authors is to seek a generic approach for first creating a Normalized Macroscopic Fundamental Diagram (NMFD) representative of the whole network using data from several collection locations. The NMFD will then be utilized as a normalized structure to retrieve the FD of all other network links using minimal information gathered from network geometry and accessible physical facts (like speed limits).

The suggested technique entails determining the similarity between some network links based on their measured data. This knowledge then helps build a representation of general behaviour. In that sense, the NMFD emerges from the clustering-based reconstruction of pertinent information from measured data.

The described method converts the original data into two-dimensional signals. By treating data as images, their classification and processing allow using FCD to map the cluster family back towards the links/roads that lack sensors.

For any traffic network covered by ILDs, many roads (links) have available measurements, and some other links exist without sensing capabilities. In addition, because density cannot always be measured directly, the relationship between densities and flows must occasionally be inferred indirectly from occupancy.

This article describes a way to estimate the traffic state in these regions without sensors, using FCD to obtain the speed of vehicles on these roads.

It is common knowledge that the following expressions denote the flow Φ:

$$\Phi(\overline{\upsilon},\overline{\varpi},\rho) = \{\overline{\upsilon}\rho, \forall\rho \leq \rho_c\} \tag{2.1}$$

$$\Phi(\overline{\upsilon},\overline{\varpi},\rho) = \{\overline{\varpi}(\rho - \rho_{max}), \forall\rho > \rho_c\} \tag{2.2}$$

In these expressions, $\overline{\upsilon}$ and $\overline{\varpi}$ are the averages of the MFD's free-flow and reverse (congestion) wave speeds, respectively, ρ is the traffic density, and ρ_{max} is the maximal density. The preceding equation system defines the simplest triangular form of the FD, represented by three parameters: $\overline{\upsilon}$, $\overline{\varpi}$, and ρ_{max}.

The value of the critical density ρ_c, reached during maximum flow Φ_{max}, is approximately given by:

$$\overline{\upsilon}\rho_c = \overline{\varpi}(\rho_c - \rho_{max}), \forall\overline{\upsilon},\overline{\varpi} > 0 \Leftrightarrow \rho_c = \frac{\overline{\varpi}\rho_{max}}{\overline{\upsilon}+\overline{\varpi}} \tag{2.3}$$

Consequently, the maximum flow can be obtained by:

$$\Phi_{max} = \overline{\upsilon}\rho_c = \frac{\overline{\upsilon}\,\overline{\varpi}\rho_{max}}{\overline{\upsilon}+\overline{\varpi}} \tag{2.4}$$

The maximal density ρ_{max} can be appropriately estimated from the roads' geometry. So, for estimating the FD, it is only necessary to discover the two remaining parameters, $\overline{\upsilon}$ and $\overline{\varpi}$. When road sensors are available, estimating such parameters by gathering flow and speed data (eventually also using the occupancy) is simple. The article describes a solution to derive FDs in places where ILDs are unavailable, but the average speed can be inferred via FCD.

The steps of this method are numbered as follows:

1. Data processing through an image-based procedure: transforming raw data to a rounded matrix, image building, resizing and filtering for outliers removal;

2. Information retrieval strategy via spatial distribution of similarity within network links based on their properties (street capacity, name, number of lanes) and Group merging;
3. NMFD construction: Alpha scaling to (density, flows) space (ρ, Φ) and normalization procedure that enables the formulation of new functions to be mapped to a specific network link;
4. Definition of Street Fundamental Diagram (SFD) from FCD velocity under NMFD conditions.

For each sample time t, raw data from a sensor on a link i consists of a pair in the format $(occ, \Phi)_t$. Hence, being m the number of measurements, the raw data of a given sensor on a link i is given by $D_i = [(occ_i, \Phi_i)_1, (occ_i, \Phi_i)_2, ..., (occ_i, \Phi_i)_m]$.

The transformation enables mapping from D to a new three-dimensional signal in (x, y, z), where x and y are integer values for occupancy and flows, respectively, and z values are proportional to the number of data points repetitions. Accordingly, the raw sensor data is processed by rounding the values for their posterior matrix localisation. The coordinates of each pixel thus directly indicate the data point's position in space (ρ, Φ), and its intensity provides a data-frequency-based construction of the new space. This transformation eliminates the effects of sample times on the MFD shape.

Then comes the removal of outliers via simple image segmentation. This process consists of partitioning the image into parts or regions based on the characteristics of its pixels. For instance, one way to find regions in an image is to look up for abrupt discontinuities in pixel values, which often denote edges. A different approach is partitioning the image into sections based on colour values. A well-known segmentation technique is the Otsu method, which can be performed without any threshold or with Multithreshold. In the first case, the Otsu method calculates the image's probability density functions and then uses the resulting information to segment the image into multiple regions. The second case uses multiple threshold values to segment the image. The Otsu method finds the first threshold value that separates the image into two regions, and then this process can be repeated to find additional threshold values.

The resulting images must be scaled to build a comparable set of images. Resizing is a standard image processing operation that offers a solid foundation for pattern identification. The matrix's conversion to grayscale is also an implicit technique. Even if the maximum values for occupancy varied within raw data, square matrices of the same size are generated.

This procedure completes the first step of the described method. Next comes the process of merging images based on their similarity.

The authors chose the IMage Euclidean Distance (IMED) to quantify image similarity. IMED considers the spatial relationships of pixels as opposed to the conventional Euclidean distance, therefore being resilient to minor image disturbances. They argue that IMED is the only intuitively plausible Euclidean distance for images. This technique is relatively efficient by involving a transformation referred to as the Standardizing Transform (ST), a domain-smoothing transform.

A merging procedure is performed on the photos with a high degree of similarity, suggesting that they belong to the same type of road within the network and may be portrayed by the same representative MFD. This process determines pertinent clusters for the dynamic identification of the roadways.

Clustering aims to identify natural groupings of data from an extensive dataset to produce a concise representation of a system's behaviour. An NMFD can then be built based on the network's representative data. Two clusters are expected for each regime (free flow and congested). Because clustering is an exploratory analytical approach, performing several replications is convenient. The authors used the K-means++ algorithm to initialize the seeds, which employs a heuristic to locate centroid seeds for k-means clustering. The distance function used in the cluster was the traditional euclidean distance. This dissertation intends to experiment with different techniques within this method, such as using IMED as a metric instead or exploring other clustering algorithms.

Up to this point, the procedure has drawn the major features' locations in the occupancy occ(%) vs flow (Φ) space. By establishing a scaling α parameter, it is possible to transfer the actual sensor data to the density (ρ) vs (Φ) space.

To this aim, the maximum occupancy percentage occ_{max} is mapped to the maximum density ρ_{max}, assuming that the free flow speed v_{ff} equals the average speed v_0 before attaining the maximum flux Φ_{max} at that maximum occupancy.

The density mapping process begins with the following relationship:

$$\Phi = \upsilon * occ \tag{2.5}$$

It will become evident after a few calculations that:

$$\upsilon = \frac{\|\Phi\|}{\Phi * occ} \tag{2.6}$$

The scaling factor α that relates both speeds is given by:

$$\alpha = \frac{\upsilon}{\upsilon_{ff}} = \frac{\frac{\|\Phi\|}{\Phi * occ}}{\upsilon_{ff}} \tag{2.7}$$

Considering a simple relationship as $\rho = \alpha * occ$, the density ρ is expressed in terms of flow Φ and occupancy occ as:

$$\rho = \frac{\frac{\|\Phi\|}{\Phi * occ}}{\upsilon_{ff}} * occ \tag{2.8}$$

After scaling the data to the (ρ, Φ) space, the Representative MFD can be normalised. The MFD is considered well-defined if the free flow speed υ_{ff}, the backward wave speed ω and the maximum flow Φ_{max} are clear.

The goal is to have a spatial distribution of vehicle density and derive an analytical description of the spatial distribution of congestion. Now, normalisation of the entire MFD must be performed under ρ_{max} as follows, starting by defining:

$$\rho_{norm} = \frac{\rho}{\rho_{max}}, \Phi_{norm} = \frac{\Phi}{\Phi_{max}} \tag{2.9}$$

As a result of this normalisation, $\rho_{norm} \in [0,1]$, and $\Phi_{norm} \in [0,1]$. The normalisation of $\overline{\upsilon}$ and $\overline{\omega}$ results in the expressions:

$$\overline{\upsilon}_{norm} = \frac{\overline{\upsilon}\rho_{max}}{\Phi_{max}} = A\overline{\upsilon} \tag{2.10}$$

$$\overline{\omega}_{norm} = \frac{\overline{\upsilon}+\overline{\omega}}{\overline{\upsilon}} = \beta(\overline{\upsilon},\overline{\omega}) \tag{2.11}$$

Then the NMFD is complete, based on the expressions:

$$\Phi_{norm} = A\overline{\upsilon}_{norm}\rho_{norm} \tag{2.12}$$

$$\Phi_{norm} = \beta(\rho_{norm}-1) \tag{2.13}$$

Finally, the last step of the described method consists of using the speed derived from FCD to build the specific FD of a given street. This data allows mapping back the cluster family towards the links/roads where sensors are missing.

Assuming that the speed $\overline{\upsilon_j}$ for the link j is known, it is possible to obtain the values for $\overline{\omega_j}$, by manipulating the equations (2.11):

$$\overline{\omega}_j = \overline{\upsilon}_j\overline{\omega}_{norm} - \overline{\upsilon}_j \tag{2.14}$$

After obtaining the values for $\overline{\upsilon_j}$ and $\overline{\omega_j}$, it is finally possible to calculate the critical density in link j, ρ_{cj}, given by the formula (2.3).

It is then simple to calculate the maximum flow Φ_{maxj} using the formula (2.4).

In summary, the method described excels at estimating a "normalised" MFD, from which the FDs of each traffic intersection can be derived. It is based on image classification techniques and uses FCD to map the cluster family back to the roads without sensors. The benefit of using image-based solutions over statistical models relies on the indirect incorporation of the measurement frequency in image construction rather than using initial matching curves that induce a first approximation.

Chapter 3

Problem and Proposed Solution

This chapter clarifies the problem addressed in this dissertation, right in section Problem Definition. The Methodology section describes an approach for producing the Digital Twin. This first semester has already seen the implementation of a preliminary version of this methodology. Finally, the Work Plan section outlines the numerous stages to be taken during this work's development and the associated expected deadlines.

3.1 Problem Definition

As mentioned before, this work's primary goal is to create a DT of the VCI highway, which aims to reflect the performance of this road through the simulation of a virtual space, thus allowing its monitoring, analysis, testing and optimization. ARMIS will provide direct access to data from inductive-loop detectors underneath the VCI pavement, which will be used to calibrate the digital model in real-time. The aim is to achieve the greatest possible reliability, ensuring that the digital model accurately represents reality.

This task becomes challenging owing to one of the most severe issues with stationary detectors like ILDs: their restricted network coverage. In regions without sensors, information is scarce or poor, making it difficult to digitally replicate the entire VCI network.

Thus, this dissertation aims to investigate strategies for overcoming this barrier, allowing the building of a dependable Digital Twin for the VCI network.

3.2 Methodology

The DT will be developed in SUMO (Simulation of Urban MObility), an open-source, highly portable and continuous road traffic simulation package designed to handle large road networks.

SUMO simulates the behaviour of individual vehicles (microscopic level) and their interactions with each other and the road network. It allows for investigating several traffic-related phenomena, such as traffic flow, congestion, accidents, and the effects of different traffic management tactics. The software is highly configurable and capable of modelling various types of vehicles, road networks, and traffic conditions. By using it, it is possible to examine the performance of traffic control strategies and transportation systems.

The first step towards building the Digital Twin is to obtain a representation of the VCI vehicular network. For this, a highway map was obtained from OpenStreetMap, proceeding with the conversion into a SUMO network. However, the representation also contained unnecessary information, which could harm the model's behaviour, like roads for vehicle classes of no interest to the simulation. The steps below describe the map-cleaning process:

1. Convert the map into a network and remove unnecessary lanes of no interest to the simulation (such as train or pedestrian roads) by running the following command:

```
netconvert --osm ./data/vci.osm -o ./data/vci.net.xml --remove-edges.by-
    vclass private,emergency,authority,army,vip,pedestrian,hov,coach,delivery
    ,moped,bicycle,evehicle,tram,rail_urban,rail,rail_electric,rail_fast,ship
```

2. Remove non-VCI roads from the map using the graphical user interface NETedit;
3. Remove dangling nodes and isolated edges with the command:

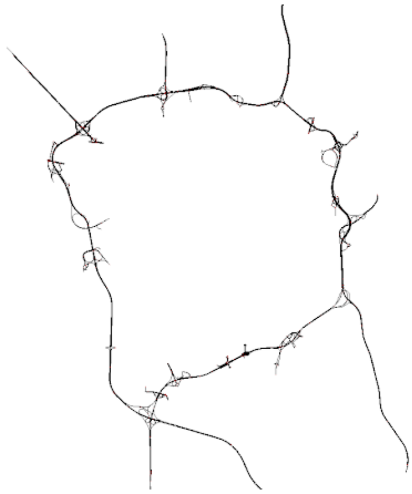
```
netconvert -s ./data/vci.net.xml -o ./data/vci.net.xml --remove-edges.
    isolated true
```

Figure 3.1a exemplifies a VCI network already processed, composed of the main roads and the small roads derived from them.

The next step is to create the OD matrix, which denotes all combinations of Origin-Destination pairs in this network. An automatic way of recognising these pairs is needed, implemented as follows:

1. Create a new map version where only the VCI major roads remain (Figure 3.1b);
2. Analyse each of the network nodes, characterising them as follows:
    a. If a node contains at least one outgoing edge but no incoming, it is an entry node;
    b. If a node contains at least one incoming edge but no outgoing, it is an exit node;
3. After grouping all the entry and exit nodes, perform the combinations, forming the OD pairs.

(a) VCI Simulation Network



(b) VCI Main Roads

Figure 3.1: The two VCI maps used in the digital model

Next, it is necessary to prepare several simulation scenarios for optimisation, defining the vehicles and their routes. Each OD pair is associated with a number N of vehicles that will trace their route based on that origin and destination. There should be only one possible route for each OD pair, as the VCI is a circular network, which is pre-calculated before running the simulation. Considering that each sensor has a specific number of routes that pass through it, and it is possible to derive the total volume of cars that pass by each sensor in a given time, a possible initial case for optimisation is established. It consists of distributing the sensor values equally across all OD pairs whose route passes through that sensor. Figure 3.2 illustrates this strategy for deriving the initial optimisation case. Based on this case, it is possible to define other scenarios equivalent, for example, to 25%, 50% or 75% of the initial flow. Throughout this work, other methods for deriving an initial case for optimisation may be defined.

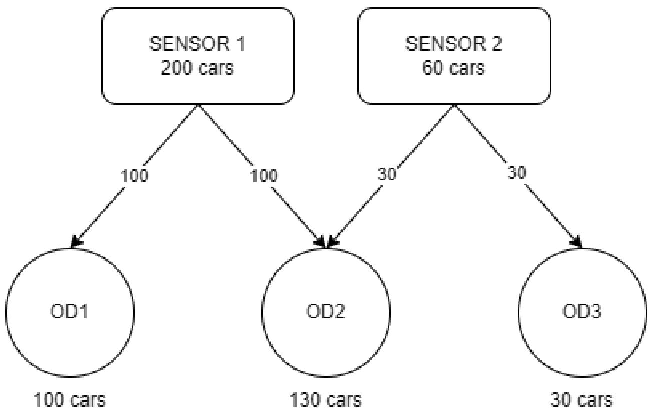


Figure 3.2: Strategy for deriving the initial case of optimization

It is required to equip SUMO with sensors in order to gather the data produced by the simulation. These sensors must be positioned on the map according to the position of the actual ILDs.

In real life, some sensors measure traffic in both directions. This is not possible in SUMO, so a sensor is needed for each lane. Therefore, further processing is required to group these data in both directions.

After preparing the real and simulated data, it is necessary to compare them, leading to the last step of DT creation: model calibration. ILDs provide several metrics, like the total volume of cars that entered and left the sensor road during the observation, the arithmetic average speed and the harmonic mean speed. The real and simulated metrics can be compared by calculating an error. The smaller this error is, the closer our model is to the actual behaviour of the VCI highway.

A reasonable option is the **mean absolute error** since this measure is less sensitive to outliers, which are very frequent in inductive loop data detectors due to the difficulty of obtaining accurate and noise-free data from the sensors. This error measure results from the sum of the absolute values of the differences between the data and is given by:

$$MAE = \frac{\sum_{i=1}^{n} |y_i - x_i|}{n} = \frac{\sum_{i=1}^{n} |e_i|}{n}$$

In this formula, n is the number of observations, y is the real sensor values, x is the SUMO sensor values, and e is the resulting difference between both values.

Thus, simulation optimisation focuses on calculating the error for each generated scenario. The scenario closest to reality is the one with the slightest error.

That said, the digital model's calibration phase ends, and this work's new stage begins, responsible for generating synthetic data in places devoid of sensors.

It is then necessary to incorporate the created data into the Digital Twin for validation. Note that the digital model's calibration and the synthetic data's validation are cyclical processes based on several experiments.

Finally, once the Digital Twin presents a high fidelity to the reality of the VCI highway and the data generated is sufficiently precise, the last phase begins, based on integrating the Digital Twin into the *Next* platform from the company ARMIS.

The following figure (3.3) depicts the pipeline of this work, as described in this section:

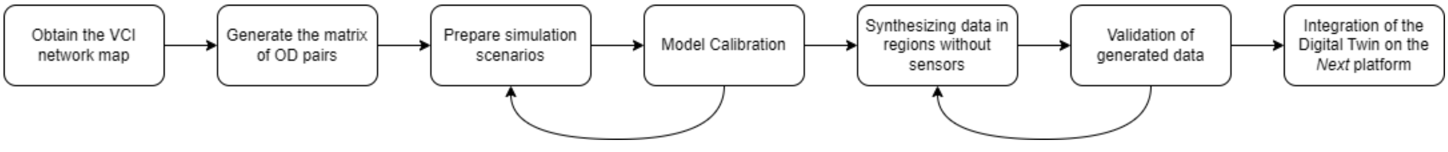


Figure 3.3: Pipeline of the work of this dissertation

3.3 Work Plan

This section establishes a work plan to improve the dissertation process's organisation.

The initial task seeks a better knowledge of the topic under study through searching and reading related articles. The advancement of this task took place mainly at the beginning of this year, being in progress until the second half of February. Subsequent comes the understanding of the *Next* platform developed by ARMIS, which this work intends to complement. This task includes the first visits to the company, aiming to comprehend its environment and technologies.

Next comes the scrutiny of the data from the VCI sensors made available by the company. This task will be crucial in understanding the data type this work will explore. It should take up the entire month of March. Somewhere in the middle of that month, the development of the Digital Twin of the VCI network also begins, which includes the model calibration process. It is scheduled to run through most of the semester, ending at the end of May.

The application of data synthesis techniques in locations bereft of sensors begins in mid-April, with a duration of one month. Afterwards, validating the generated data through its incorporation in the Digital Twin is necessary. The final two weeks of May should see the completion of this procedure. Finally, the final dissertation document write-up will be June's only focus.

The following image (3.4) illustrates this plan through a Gantt chart:

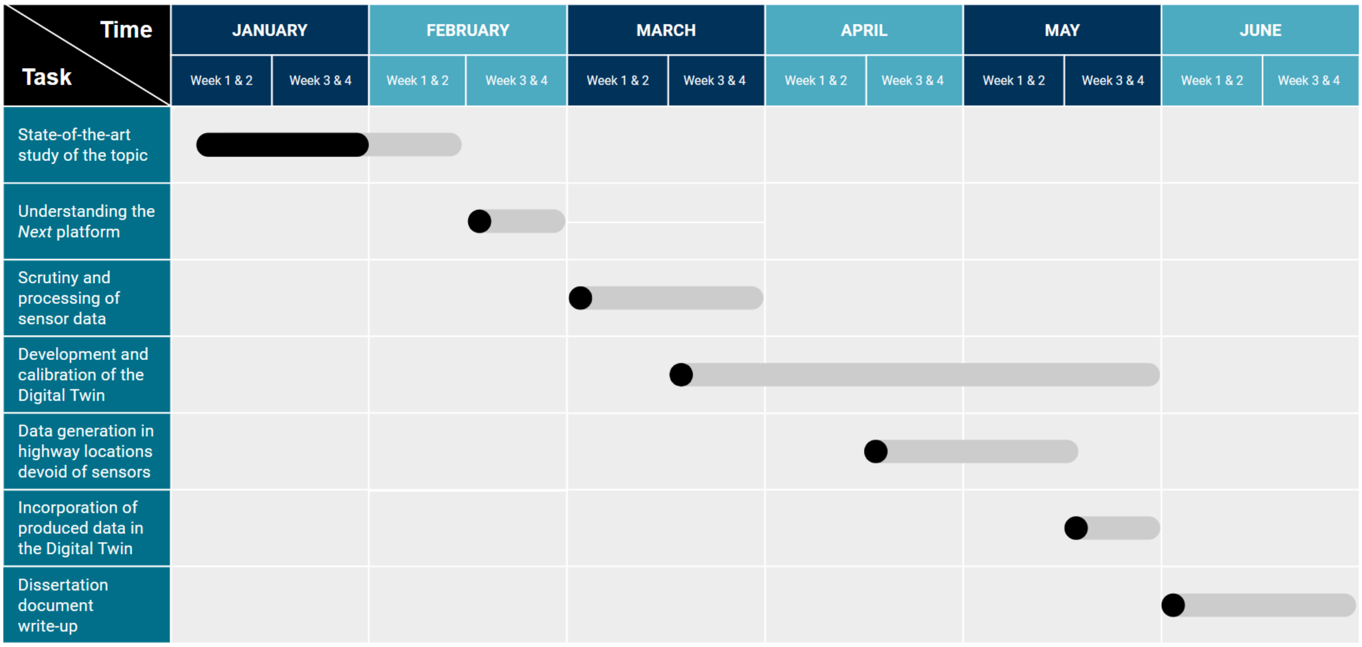


Figure 3.4: Dissertation Work Plan

Chapter 4

Conclusions and Future Work

The work developed during this phase of preparation for the dissertation proved valuable, allowing a better understanding of the topic under study and a better definition of the objectives of this project. It also allowed tracing a specific course, which will help guide this dissertation's development. As a result, the upcoming semester may get off to a strong start because this prior effort allowed defining strategies for overcoming several of the project's challenges.

Regarding future work, the next steps in the evolution of Digital Twins will be related to the definition of techniques for their construction based on the principle of modularity. One of the leading research challenges is the lack of a standard methodology for developing this tool. Therefore, it is of value to explore modelling approaches that allow deriving a criterion of auto-detection of components that can be used (and reused) for creating DTs applied to different systems or processes.

The following section, Overview, summarizes the content of this document, followed by the SMART Analysis and SWOT Analysis for this project.

4.1 Overview

In short, this document brought the reader closer to the context of this dissertation and defined its main objectives. It explored different familiar matters of the subject under investigation. The term Digital Twin proved to be quite contested in the literature, with ambiguous definitions. This work sought to eliminate these misconceptions and clearly define their benefits, challenges and enabling technologies. It described the field in which this dissertation functions, ITS, and discussed the many forms of traffic data and the essential components for representing it, such as the Fundamental Diagrams.

Afterwards, the document explained a method to solve the problem of limited coverage of fixed sensors. It also proceeded to describe a methodology for developing the VCI's Digital Twin based on some work produced in this first semester.

Finally, it has established a work plan and will end with the SMART and SWOT analysis of the project, depicted in the following two sections.

4.2 SMART Analysis

The SMART analysis methodology evaluates a project's goals and ensures they are well-defined and attainable. It uses the SMART criteria (Specific, Measurable, Achievable, Relevant, and Time-bound) to assess the objectives and determine if they are clear, measurable, and realistic.

This project is specific as it promises to create a trustworthy Digital Twin for the VCI network by carefully addressing sensorless locations.

It is measurable, seeking to obtain an insignificant error in model calibration and synthetic data generation.

It is achievable since the model will be validated using actual data from ILDs placed along the VCI highway provided by ARMIS.

The company's interest makes it relevant, in addition to promoting this new technology in the ITS field.

Finally, it is limited in time, bearing in mind that the work must be completed by June.

The following figure (4.1) visually recaps this analysis:

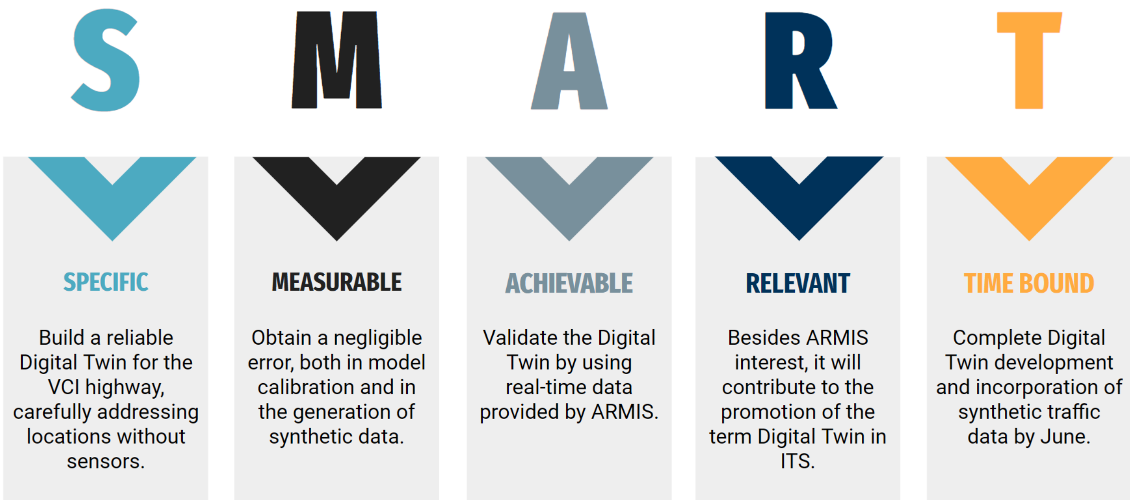


Figure 4.1: SMART analysis of the project

4.3 SWOT Analysis

A SWOT analysis is a strategic planning method that helps identify the Strengths, Weaknesses, Opportunities, and Threats of a project. The information gathered through this process aids in developing strategies for tackling the identified challenges and seizing the pinpointed opportunities.

Among the strengths, ARMIS's interest, the project's practical application, and its scientific and contemporary nature stand out. A considerable number of sensors along the VCI also constitutes a strength, allowing a more reliable characterization of traffic on this highway.

The fact that it only uses data from one type of source is a weakness, resulting in insufficient data in areas devoid of sensors. Besides, the Digital Twin resulting from this work will be limited to the VCI highway, therefore being specific to this network.

The modernization of traffic control systems and the gradual introduction of the Digital Twin concept in this industry are opportunities to be seized. Furthermore, recent improvements in the speed and quality of the data collection process favour the implementation of this new tool.

Finally, among the threats, the difficulty in obtaining accurate data and the effort associated with understanding the *Next* platform stand out. These processes and future difficulties can lead to non-compliance with the deadlines established in the work plan.

The following figure (4.2) presents a condensed version of this analysis:

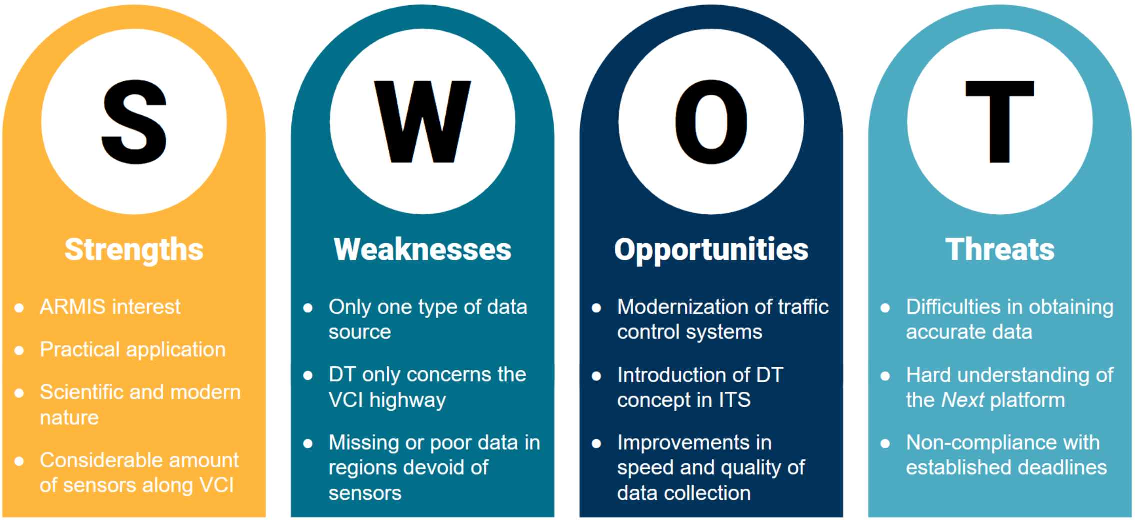


Figure 4.2: SWOT analysis of the project

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