TÉCNICO LISBOA

Autonomous Vehicles Ontology

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Thesis to obtain the Master of Science Degree in

Information Systems and Computer Engineering

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September 2021

Acknowledgments

I would like to thank my dissertation supervisors Professor Miguel Mira da Silva and Professor Flavia Maria Santoro for all their guidance and time throughout this process.

I would like to thank my friends who have supported me.

I would like to thank my boyfriend who has encouraged me constantly.

Lastly I thank my family, who are my rock and without whom this dissertation would not have been made, as they supported me through everything leading up to this moment.

To every single one of you, thank you.

Abstract

Autonomous vehicles are one of the most interesting and active topics of investigation nowadays, with many research centres and companies on the transportation sector investing in its advancement. In recent years they have become a hot topic among the general public, and science has been making strides in order to turn them into a reality, and that reality is closer than ever. However, many researchers are developing work in parallel, and many in similar areas. With so many researchers working on the topic, a common framework to refer to concepts within this domain would be quite useful, and would allow the scientists, engineers, and other professionals working in this area to build upon each others´ work. With this in mind, we have performed a systematic Literature Review in order to raise relevant concepts on the topic, and extracted information from the sources obtained. We then developed an ontology - an explicit formal specification of the terms in a given domain and the relations between them - which aims to establish a common reference within the domain.

Keywords

Autonomous; Driverless; Cars; Vehicles; Ontology; Model; Concepts.

Resumo

Veículos autónomos são uns dos tópicos de investigação mais activos e interessantes actualmente, e existem vários centros de pesquisas e várias empresas no setor de transportes a investir na área. Recentemente tornaram-se fonte de interesse para o público, e a ciência tem feito avanços com o intuito de tornar esta tecnologia em realidade. No entanto, existem vários investigadores a desenvolver trabalho nesta área. Era útil a existência de uma framework para ajudar na referência a conceitos dentro desta área, tornando possível aos cientistas, engenheiros e outros profissionais a trabalhar nesta área construir sobre o trabalhos uns dos outros. Com este objetivo, realizámos uma Revisão de Literatura sistemática, de forma a recolher conceitos relevantes do tópico, e extraimos informação das fontes obtidas. A partir destes dados desenvolvemos uma ontologia - uma especificação formal explícita dos termos num dado domínio, bem como as relações entre eles - que tem o intuíto de estabelecer uma referência comum dentro do domínio.

Palavras Chave

Autónomos; Carros; Veículos; Ontologia; Modelo; Conceitos.

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Acronyms

AV Autonomous Vehicle

SABiO Systematic Approach for Building Ontologies

SLR Systematic Literature Review

1

Introduction

Contents

Vehicle automation is a sector that has steadily been gathering interest worldwide. While it has long captured the imagination of the general public, in recent years the science has caught up to science fiction, and the technology is in place to permit autonomous transportation as a reality. Starting in the 1980's [1], it has been the subject of much study and development.

A driverless car is an unmanned vehicle that is capable of maneuvering without human input but utilizes the support of several sophisticated sub-systems and devices [2]. Nowadays the crucial factor in vehicle automation is consumer adoption, and how readily the general public accepts Autonomous Vehicle (AV)s as a reality. Automotive companies would benefit from knowing which factors influence AV adoption by the public.

Consumer adoption is not, however, the only factor for success for AVs. For example, to circulate with safety, AVs will need an accurate understanding of its surrounding, the state of the infrastructure upon which it is moving, and in order to ensure safety the road operators need to have detailed and current knowledge of the vehicles [3]. While AVs can be programmed to communicate with other elements and actors in their environment, they are capable of operating by gathering information about their surroundings using sensors [4].

If accepted widely in our society, AV can positively impact many areas of our life. Transportation equity can be greatly improved [5], as long as how the mobility model implemented impacts everyone is considered, and not only the ones with financial access (by focusing less on private ownership and more on public transit, for example) [6].

They have also been shown to benefit traffic safety and traffic flow [5]. They might, however, negatively affect land use, by causing urban sprawl (i.e. migrating to areas with lower density and consequently spreading cities) as transportation becomes easier to access and use, and possibly cause the increased use of transportation as it becomes more accessible, causing more air pollution and greenhouse gas emissions [7].

AVs can positively affect the use of car-sharing, whereby vehicles operate as short-term rentals, where members can rent a vehicle, drive to a nearby destination, and then release the rental when finished with their trip. These programs can improve the environmental footprint of transportation, as well as land use, by allowing reduced vehicle ownership, reduced parking needs, and possibly reducing the distances vehicles travel [8].

AVs can solve several transportation-related issues, such as congestion, dependency on oil resources, scarcity of parking, noise and air pollution, as well as bridge the gap in mobility between urban and rural areas, depending on how well they are accepted by the public [9].

As connected vehicles can communicate, send and receive data, AVs can have a significant impact on the reduction of traffic accidents, congestion, and overall traffic safety, by bringing artificial intelligence and enhanced communication between the different players on the road (pedestrians, passengers, and vehicles). They can provide mobility to different sections of the community, such as children, seniors, and mobility-impaired individuals [5].

However, the technological development already made currently outpaces the social acceptance and infrastructural support AVs possess. A consensus on how to handle AVs among all the players involved in this sector would be most useful.

Given the success of and the interest in the field of AV, investigation in this subject has been growing exponentially over the years (see figure 3.4). If researchers had a common reference, they would be able to build upon one another's research to a higher degree. The existence of an overview of AV research would also aid those in charge of AV-related endeavors (such as putting in place the infrastructure necessary to house AV), as they need to have a fairly complete picture of the general status of the field. With this goal, we propose to create an ontology for AVs, finding and organizing concepts from its entire domain. To do this, we employed the Systematic Approach for Building Ontologies (SABiO) methodology [10] and used the systematic literature review [11] to support one of its processes.

1.1 Organization of the Document

This thesis is organized as follows: chapter 2 provides a background on the methodologies used in this thesis, the SABiO methodology - Systematic Approach for Building Ontologies, and the Systematic Literature Review. In Chapter 3 we perform an Systematic Literature Review (SLR) to retrieve the relevant information to the ontology, which is composed of three phases: section 3.1, planning the review, section 3.2, conducting the review, and section 3.3 reporting the review. This acts as the knowledge acquisition process in the SABiO methodology. In chapter 4 we conduct the steps of the SABiO methodology necessary to obtain a reference ontology, with the first being purpose identification and requirements elicitation, and the second being ontology capture and formalization. We then present the ontology obtained. In Chapter 5 we validate the ontology by performing an SLR that has the purpose of identifying, in a real-life situation, analogous concepts to the ones obtained in the ontology. Finally, in Chapter 6 we present our final remarks and our intention for future work.

2

Methodologies

Contents

2.1 SABiO - Systematic Approach for Building Ontologies

An ontology is defined as an explicit formal specification of the terms in a given domain and the relations between them, and as a formal explicit description of concepts in a domain of discourse (classes), properties of each concept describing various features and attributes of the concept (slots), and restrictions on slots (facets) in [12], and as "an agreed and shared formal representation of knowledge, a model of formal specification regarding naming and definition of types, properties, and interrelationships of entities that exist in a particular domain of discourse" in [13].

Ontologies are useful for domain experts that can use them to share information in their fields, as they provide a common vocabulary for researchers, as well as a way to share a common understanding of the structure of information in the given domain. An ontology also enables reuse and analysis of domain knowledge, makes domain assumptions specific, and separates domain knowledge from operational knowledge - separating the information about the domain itself from information about given processes within the domain itself [12].

To build a structurally sound ontology, it is recommended to follow an ontology-building framework. For this research, we chose SABiO, which stands for Systematic Approach for BuIlding Ontologies [10], and is a method for building ontologies, specifically for the development of domain reference ontologies. A domain ontology is built to make the best possible description of the domain. It has been used for building several domain ontologies since its first version was published in 1997. SABiO allows for the rigorous definition of models, the identification of problems in the definition and interpretation of concepts, and recommendations for model formality improvements. Within domain ontologies, there are two types, reference ontologies (which are a type of conceptual model), and operational ontologies (which are machine-readable implementations of the reference ontology).

There are five main phases in the SABiO development process:

- **Purpose identification and requirements elicitation;** In this phase, we must identify the ontology's purpose and its intended uses, find its functional and non-functional requirements, and identify competency questions. If necessary, modularize the ontology into a set of sub-ontologies.
- **Ontology capture and formalization;** In this phase, the relevant concepts and relations should be identified and organized. This phase should be guided by the competency questions.
- **Design;** If an operational version of the ontology is to be developed, then it is necessary to implement it in a particular machine-readable ontology language (such as OWL). In this phase, technological non-functional requirements and the ontology implementation environment must be taken into account.
- **Implementation;** Regards implementing the ontology in the chosen operational language.

- **Test;** In this phase, we must verify and validate the behavior of the operational ontology. The testing phase is also guided by the competency questions, and considers mainly black-box testing, although white-box testing may also be considered.

To obtain a reference ontology, the first two activities of the development process must be accomplished. To obtain an operational ontology, all must be completed. We will be producing a reference ontology, and therefore will execute only the first two activities.

There are also support processes to these phases that are performed in parallel to the development process:

- **Knowledge acquisition process;** To execute the knowledge acquisition, we performed a Systematic Literature Review to obtain the relevant studies and extract the necessary terms and relations between said terms.

- **Reuse process;** This refers to reusing conceptualizations already established for the given domain and reusing existing ontologies for the domain, either totally or partially.

- **Documentation process;** Documenting the results of the ontology development process, as well as results from some support processes, such as evaluation.

- **Configuration management process;** The main documents proposed by SABiO must be controlled concerning changes, versions, and delivery.

- **Evaluation process;** Ontology testing is an evaluation activity. Static (.e. through technical reviews) and dynamic (i.e. running code) evaluation tests should be performed during the ontology development process.

These processes are illustrated in Fig. 2.1.

2.2 Systematic Literature Review

SLR is a research methodology that has been commonly used in the fields of medicine and science for a long time. It is not a primary study, which is an empirical study investigating a specific research question, but rather a form of secondary study. These studies review all primary studies relating to a specific research question to integrate evidence related to said specific research question.

SLR uses a well-defined methodology to identify, analyze and interpret all available evidence related to a specific research question in an unbiased way and (to a degree) repeatable. Barbara Kitchenham created guidelines that adapt this methodology to apply it to computer science research [11].

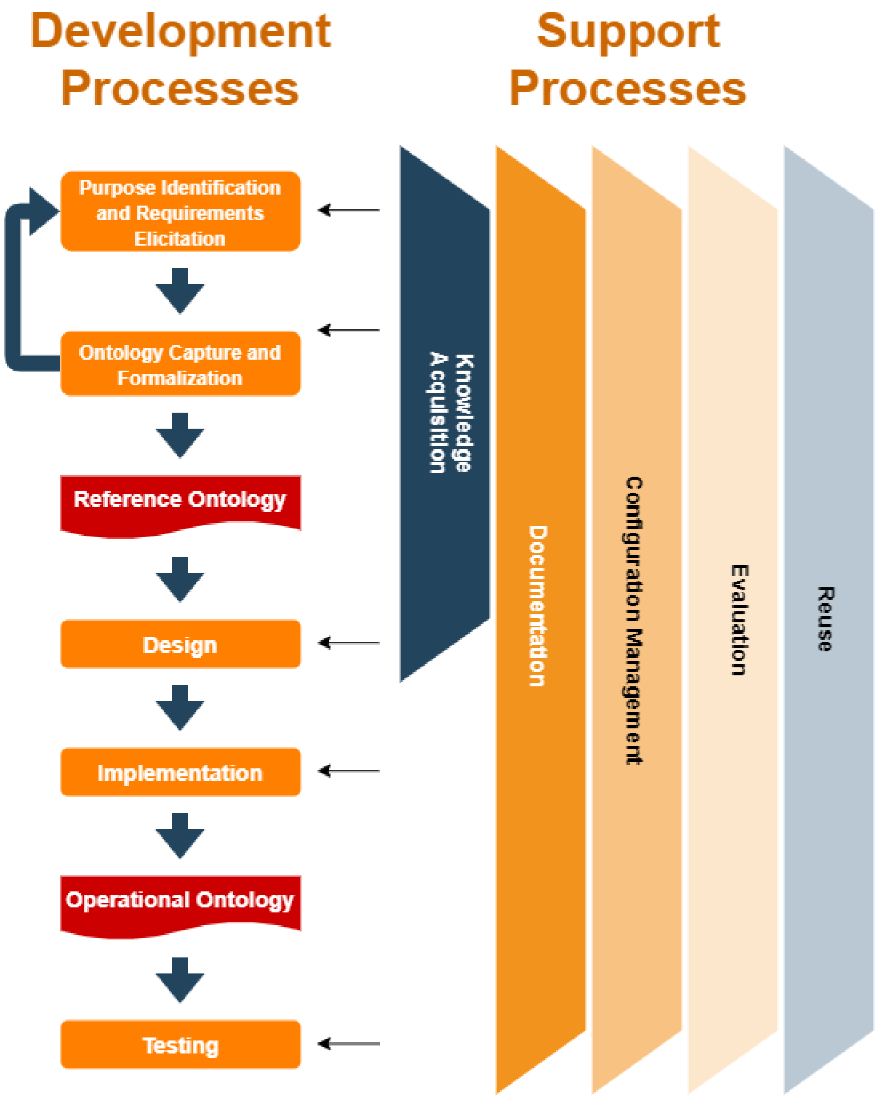

Figure 2.1: SABiO processes.

These guidelines allow researchers to accomplish several goals; to summarize existing evidence concerning a given subject, provide a framework to plan new research activities appropriately, and identify gaps in current research. A literature review must be thorough and fair to hold scientific value, and the SLR methodology provides a framework to ensure this. It comprises three phases: planning the review, conducting the review, and reporting the review:

- **Planning the review** entails confirming the need for the review in the first place, defining the research questions, and producing a review protocol defining the basic review procedures.
- **Conducting the review** consists of finding as many primary studies as possible using an unbiased search strategy. Inclusion and exclusion criteria should be defined based on the research questions and applied to the studies obtained. These criteria should also address the quality of the

studies in question. Finally, the data should be extracted and the information necessary to address the research questions must be collected.

- When **reporting the review**, the data must be collated and synthesized to answer the research questions, and the results must be presented.

These three steps, adapted to our research, are presented in Fig. 2.2.

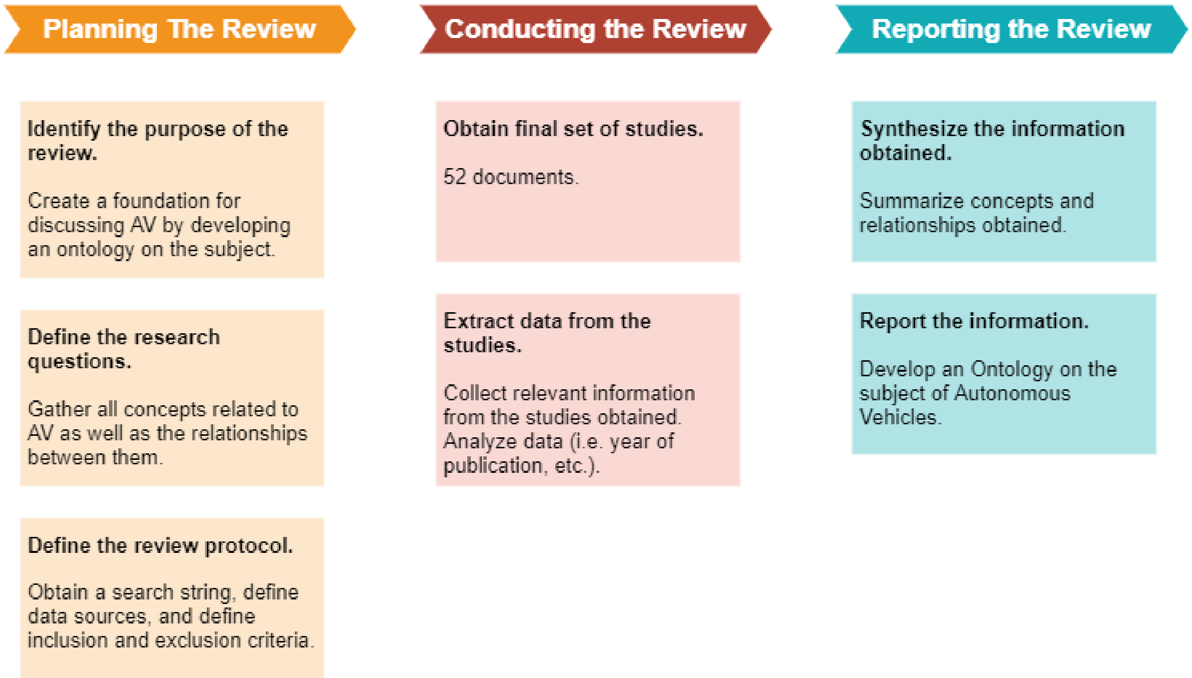

Figure 2.2: Systematic Literature Review adapted to our purposes.

3

Knowledge Acquisition

Contents

3.1 Planning the Review

This SLR serves as a supporting process to the SABiO methodology, as a knowledge acquisition method. Knowledge acquisition can be done using several sources, such as domain experts for example. A systematic methodology such as an SLR was thought to be an effective way to perform this process thoroughly. It would also be possible to objectively analyze the process, as it was done using a defined methodology.

The main motivation in carrying out this review is to provide a common foundation of knowledge for researchers developing work in the field of vehicle automation, as well as government officials who regulate transportation infrastructure. We believe that a common vocabulary between researchers would make surveying information on the AV topic much easier, as nowadays research depends on search strings and search engines - which in turn are narrow tools, limited in scope, as relevant papers may not be obtained because the right words are not included in the title.

In planning the review, we established the following research questions:

Q1: What are the main concepts related to AVs?

Q2: What are the relationships between them?

To obtain the studies, the methodology states that a search string must be derived from the research questions and used to find all the relevant documents. For this review, we defined the following search string:

(”Model” OR “Representation” OR “Ontology” OR ”Concept”) AND (”Autonomous” OR ”Driverless” OR “Self-driving”) AND (”Vehicle” OR ”Car”)

We searched the string in the title and abstracts in the data sources that allowed for it, and only in the title in those that did not provide that option. The data sources used were the following:

- **ACM Digital Library** portal.acm.org
- **EBSCO** ebsco.com/products/ebsco-discovery-service
- **IEEE Digital Library** ieeexplore.ieee.org
- **Scopus** scopus.com

To filter the studies in regards to their relevance to the topic in question and their scientific quality, we applied the inclusion and exclusion criteria we can observe in figure 3.1:

We applied these criteria to the papers obtained with the search string, and then read the abstracts in order to further cull the remaining papers. Those chosen were read in full, reaching a final set of relevant papers.

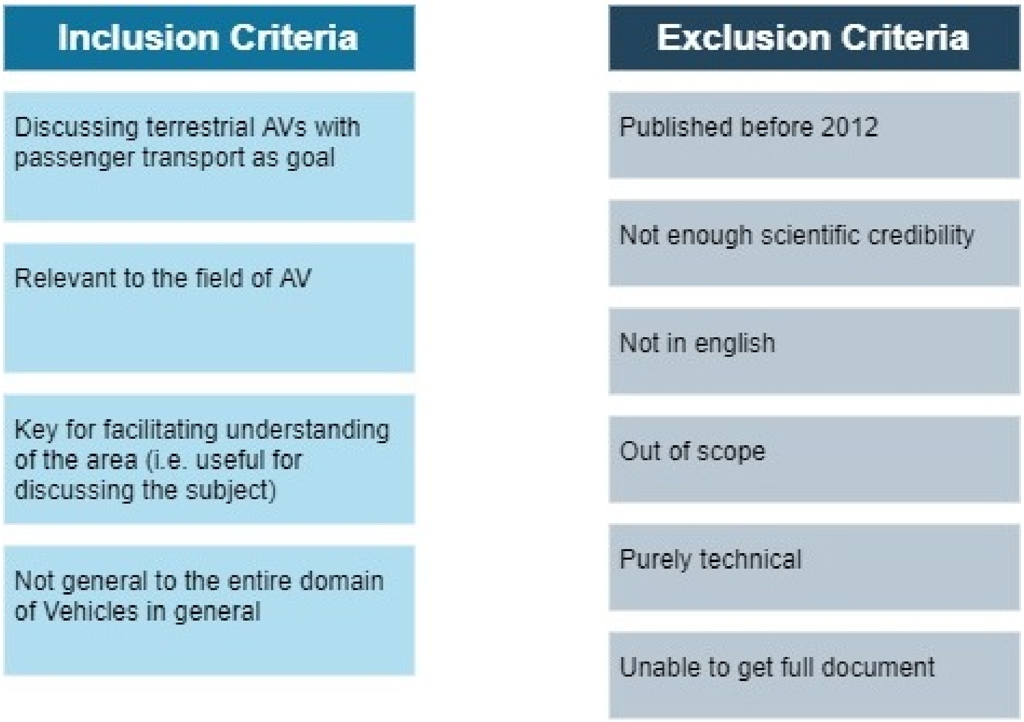

Figure 3.1: Inclusion and exclusion criteria.

In order to perform this process, we used the online tool Parsif.al, an online tool designed to support researchers in performing systematic literature reviews within the context of Software Engineering. figure 3.2 summarizes the review protocol.

3.2 Conducting the Review

In this section, we detail how we accomplished the second phase of the SLR methodology.

When we applied the search string, we got a set of 1346 documents. We eliminated duplicates and obtained 499 documents. We then read the abstracts of these documents and selected 151. Finally, we read these 151 documents fully and reached a final set of 52 papers relevant to our research. Figure 3.3 summarizes the process of selecting the relevant documents.

In appendix A we have included a table mapping the 52 final articles to the identifiers used in the rest of the text.

Figure 3.2: Review protocol.

3.2.1 Distribution of documents throughout the years

The bar graph in figure 3.4 shows the distribution of the final set of documents referring to the year of publication. We can see from the graph that research in this field has become more frequent as the years go by, indicating rising interest in this subject, with most of the papers written since 2018.

3.2.2 Distribution of documents per conference

In figure 3.5, we summarized the conferences and journals that provided multiple documents relevant to our research. Not many documents originated from the same publication, as we found that there wasn't a given journal or publication, or a small group of them, from where most documents originated.

Instead, as we matched each document to where it was published, we found most journals accounted only for one document.

We can infer that vehicle automation attracts interest from several scientific areas, as publications from many different fields deal with and publish documents about the topic, from computer engineering to the social sciences.

In this horizontal bar chart, we represent the journals that accounted for more than one document in our final set and the distribution of documents between them. For reference, the Transportation Research Record represents 4 documents, Sensors (Switzerland) represents 3, and all the others represent 2 documents.

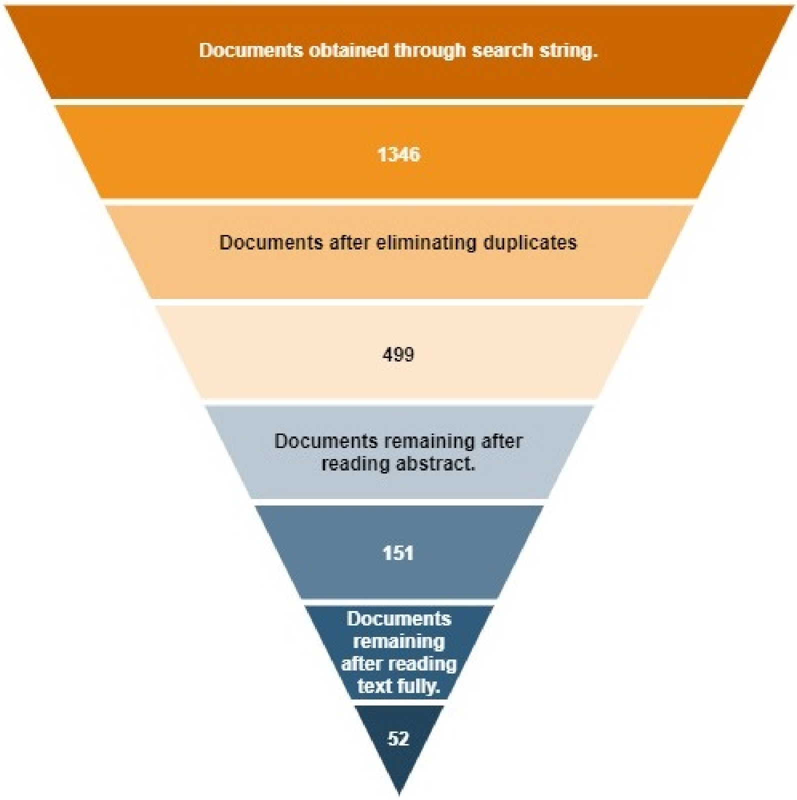

Figure 3.3: Number of documents at each phase.

3.2.3 Distribution of documents per sub-domain

In the course of developing this ontology, the need to modularize it was identified, the reason for which can be found in section section 4.1. In appendix B we have included a breakdown of which articles contribute the most to each module.

3.3 Reporting the Review

The process of extracting the information from the articles was an iterative one, comprised of 2 phases.

As the first 151 articles were read, all possible concepts were gathered. They were then each assigned to the sub-domain they most closely aligned with - the rationale for the attribution is explained in section 4.1.

Then, possible relationships between concepts were identified and validated using quotes taken from the literature consulted. This can be found in appendix C. the information retrieved from this SLR, which became the stepping stone to creating the ontology, is presented in this table.

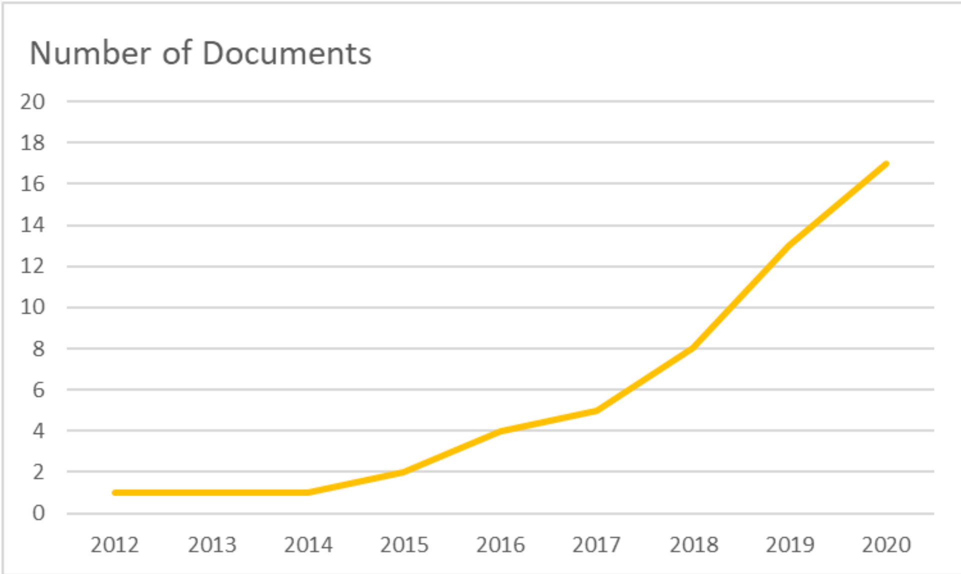

Figure 3.4: Distribution of documents per year.

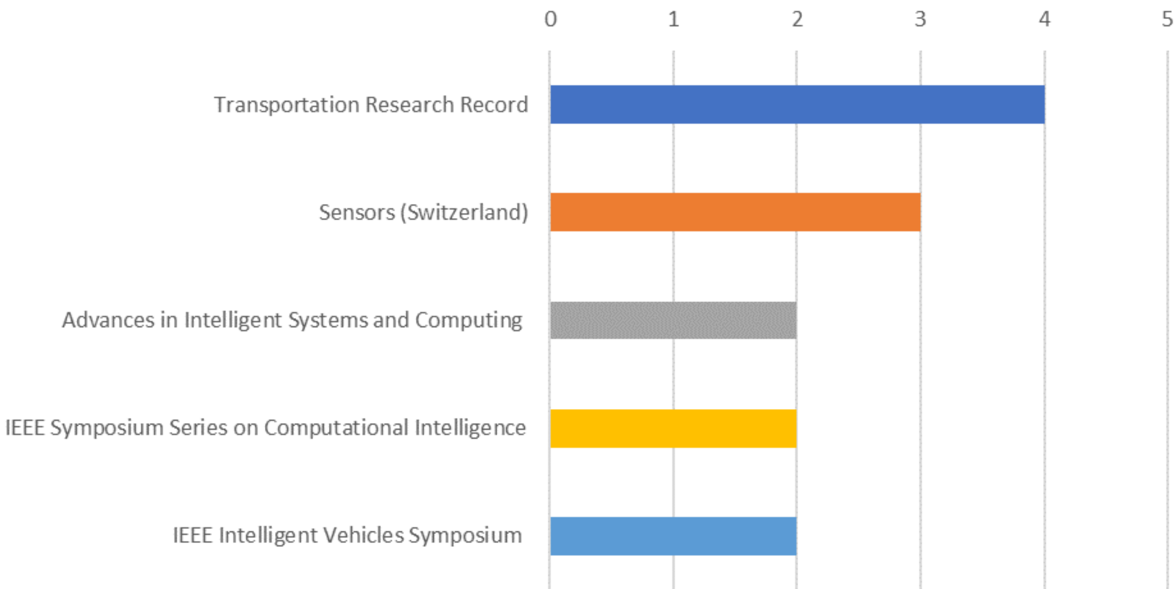

Figure 3.5: Distribution of documents per journal.

4

Executing the SABiO Methodology

Contents

4.1 Purpose Identification and Requirements Elicitation

In this chapter, we will perform the first two steps of the SABiO methodology, and by the end of it, we will have a finished reference ontology.

The initial phase of the SABiO methodology encompasses four main activities that occur continually. First, it is necessary to identify the ontology purpose and it is intended uses. Our main goal is to define a reference ontology that will provide a resource in the area of autonomous vehicles, as it is a fast-growing sector, and as such, research is being approached from many angles and by many different researchers. Hopefully, this ontology will be used by researchers to access a common language when addressing the subject of autonomous vehicles, and have the added benefit of helping people working in this field find each other's work efficiently.

Then, the ontology requirements must be identified. This was done by defining competency questions, using a middle-out strategy (writing down important questions that can then be classified into either abstract and simple questions). The following competency questions were obtained:

- **CQ1** What influences AV adoption?
- **CQ2** How can an AV be integrated into society?
- **CQ3** What constitutes the AV's environment?
- **CQ4** How does an AV sense its environment?
- **CQ5** How does an AV interact with its environment?
- **CQ6** Who are the actors interacting with AVs?
- **CQ7** What types of communication do AVs have?
- **CQ8** What kinds of AVs exist?

The last step is to identify whether a need for modularization exists, which consists of sectioning modules that can be considered separately while still being connected to other modules. The domain for this ontology is quite vast, causing the separation of the ontology into three modules: a module concerning the physical environment surrounding the vehicle (i.e. threats that may occur, infrastructure it uses); one concerning the social environment (i.e. the impacts AV will have on society); and finally components, such as the sensors with which AVs discern with its surroundings.

4.2 Ontology Capture and Formalization

We represented the relationships between concepts using UML schemas. We created different schemas for each module and developed a color code to signify to which module each concept is assigned and to help represent relationships between domains.

4.2.1 Color Coding

In these schemas, red represents the Components module, yellow represents Physical Environment, and purple represents Social Environment. White represents core concepts, the basic concepts that align with every module. Some concepts are present in more than more module because they align with both, such as high occupancy and low occupancy AVs; the vehicle itself has to physically allow high or low occupancy, but it impacts mostly how the public will interact with the AV.

The color scheme is better illustrated in figure 4.1, which denotes the modules in the Autonomous Vehicles domain. Unless it is a generalization relationship, also known as an "is a" association (e.g. Vehicle Security is a type of Security), each relationship is characterized in the schema.

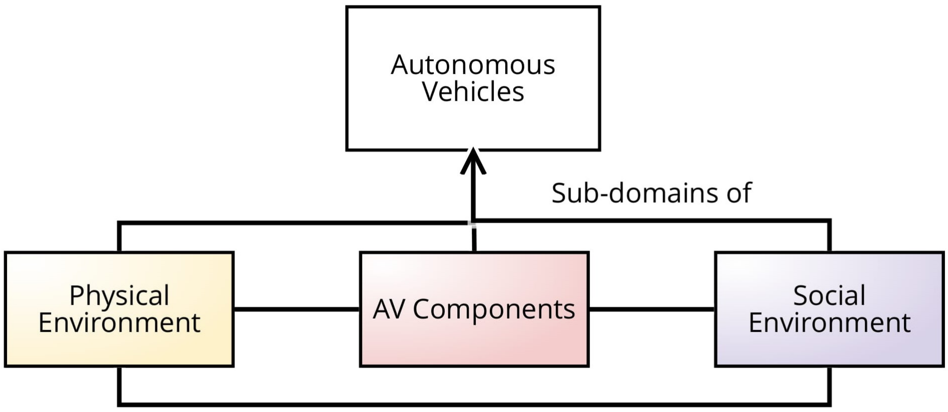

Figure 4.1: Color scheme of the different modules.

4.2.2 General Concepts

In figure 4.2, we outline the general concepts in the autonomous vehicles field. These are the concepts that must be present in every module's schema in order to connect the concepts.

The core of the ontology is the **autonomous vehicle**. It is defined as an "unmanned vehicle that is capable of maneuvering without human input but utilizes the support of several sophisticated subsystems and devices" in [2], and as an "automatic vehicle that does not require human operation and can automatically perceive the environment and make decisions" in [14]. An autonomous vehicle is a sub-type of **vehicle**, which comprises manned and unmanned vehicles. A **connected autonomous vehicle** is a sub-type of AV, in [5] it is referred to as an AV that is equipped with Internet access, and

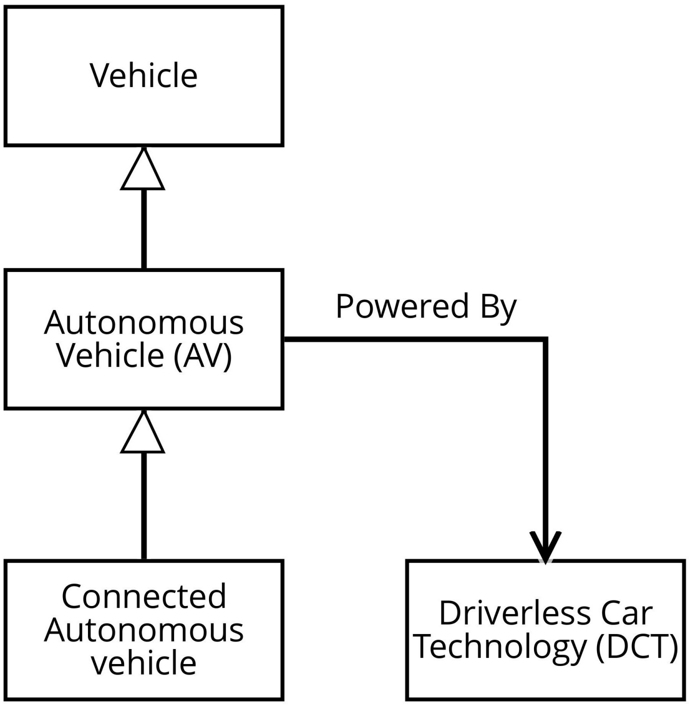

Figure 4.2: Relationship between the general concepts in the domain.

which can share access with other devices inside and outside the vehicle. **Driverless car technology** is differentiated from AVs as AVs denote the combination of the physical vehicle and the AI agent that pilots it. It is defined as a "computer-controlled AI agent(s) which can supervise, take decisions and fully manage itself without human input" [15].

4.2.3 Components Module

In figure 4.3, we detail the relationships in the Components module.

AVs are equipped with communication capabilities to communicate between vehicles or parts of the transportation system. To this end, they use either **VANET networks** or **internet networks** [16].

We also see which car parts AVs specifically need to operate: **sensors**, **actuators**, and **driver assistance systems**, as "three elements are common to all autonomous ground vehicles: sensors to perceive the environment and the own movement, on-board computers, and actuators for vehicle control" [1]. There are five types of sensors, namely **acceleration sensors**, **velocity sensors**, **GPS sensors**, **range sensing devices** such as RADAR and LIDAR [1], and **image-based sensors** such as cameras [1].

There are also five main types of driver assistance systems. We have **decision making systems**, which "have the capability to deal with complex decision environments and involve the layout of mathe-

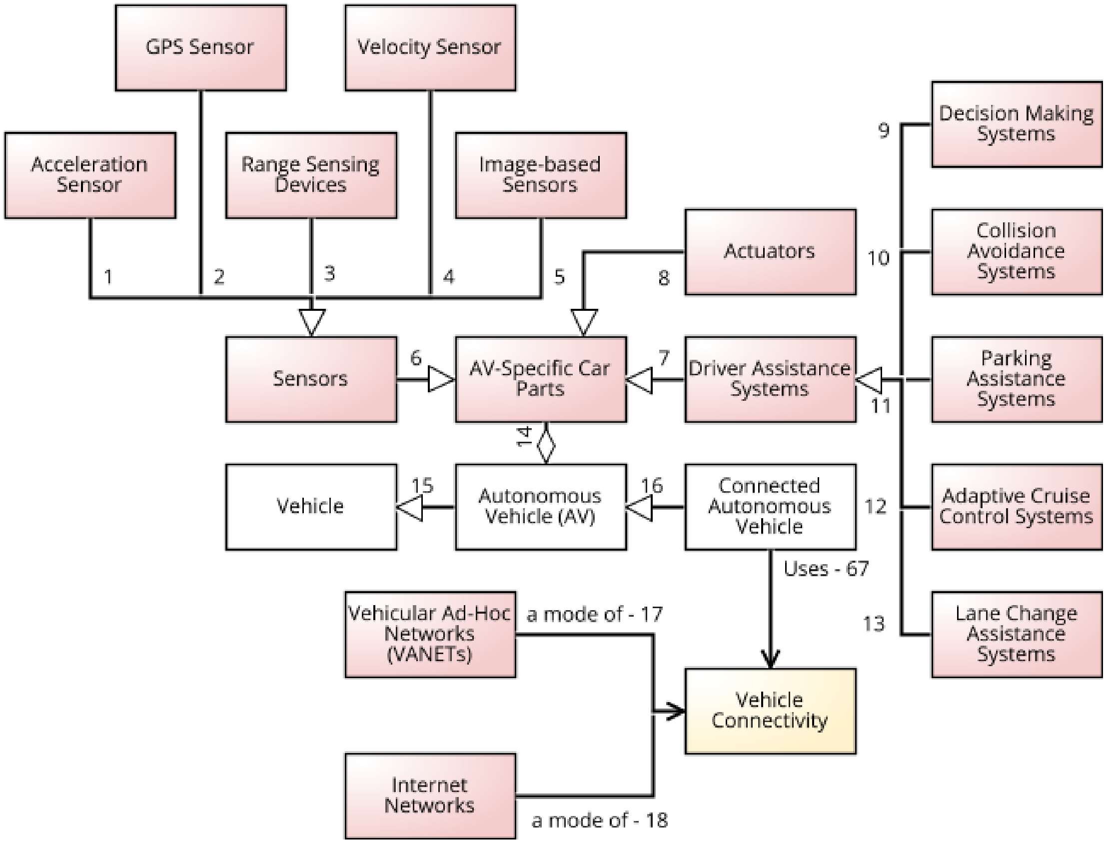

Figure 4.3: Relationship between concepts of the Components module.

matical models" [17], collision avoidance systems, parking assistance systems, adaptive cruise control systems, and lane change assistance systems [2].

4.2.4 Physical Environment Module

In figure 4.4, we represent the relationships in the Physical Environment. Most of the concepts have to do with Infrastructure, Security, and which roles exist within (autonomous) transportation. It details how many different forms for communication exist, for example, and the different levels of vehicle automation.

We represent the different roles that can be played involving AVs as **actors**. There are five types of actors - **drivers, pedestrians**, **vehicles** [18], **passengers**, and **vulnerable road users** [19].

In the components module, we saw that there are different networks AVs can use to communicate. There are also several types of communication, based on with whom the AV is connecting, such as **vehicle-to-Cloud (V2C)**, which exchanges information with a cloud system, allowing the vehicle to use information from other cloud-connected objects such as smart homes or industries such as energy,

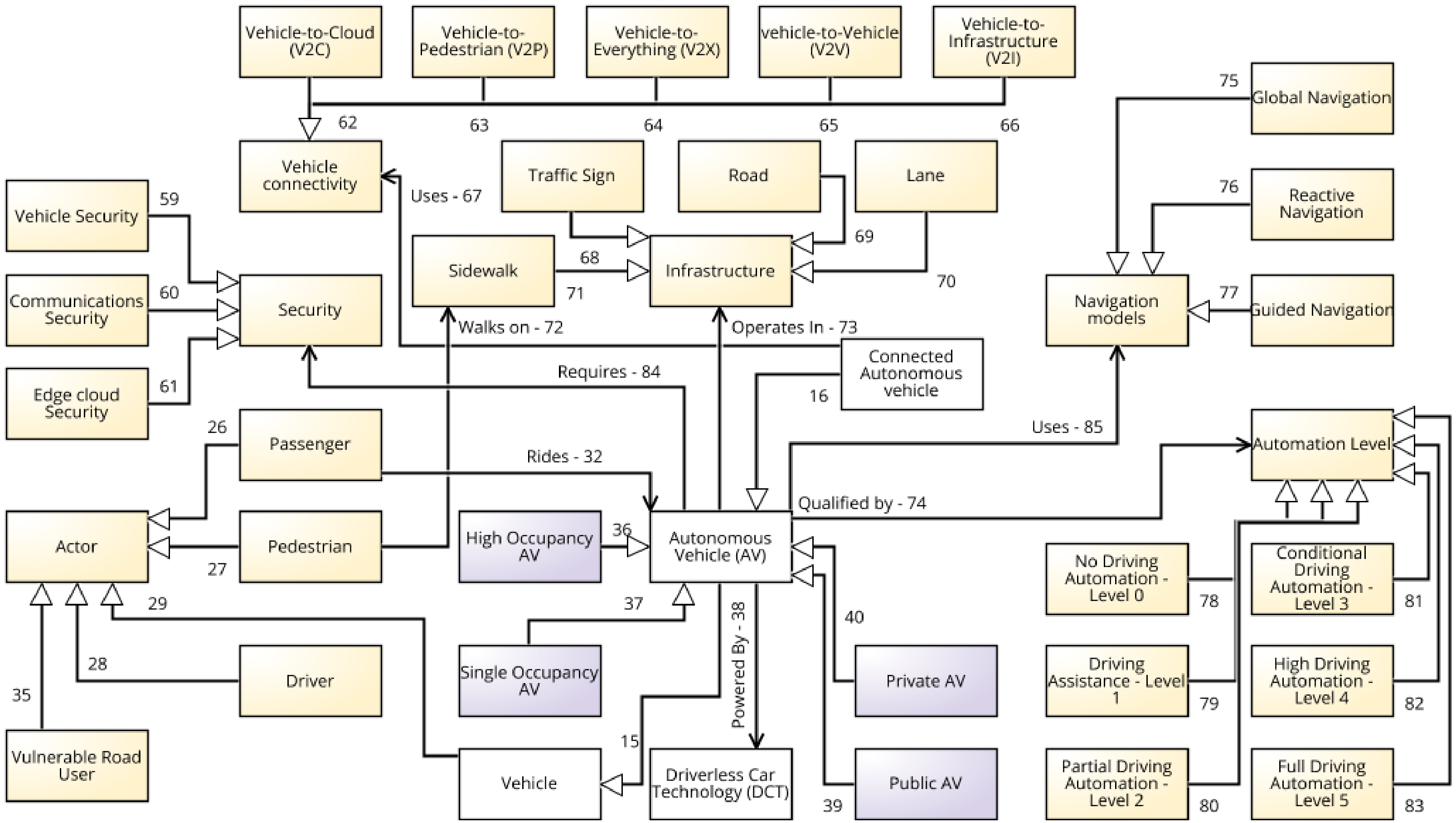

Figure 4.4: Relationship between concepts of the Physical Environment module.

transportation and to make use of the Internet of Things; **vehicle-to-Pedestrian (V2P)**, which senses information about its environment and communicates it to personal mobile devices, enabling the vehicle to communicate with pedestrians and to improve safety and mobility on the road; **Vehicle-to-Everything (V2X)**, which interconnects all types of vehicles and infrastructure systems with each another; **vehicle-to-Vehicle (V2V)**, which allows vehicles to communicate information about speed and position of surrounding vehicles to avoid accidents and ease traffic; and **vehicle-to-Infrastructure (V2I)**, used to share information about safety, mobility or environment-related conditions [5]

AVs have some possible vulnerabilities, creating the necessity of preventing them . This requires **security** to be a concern. Security is defined as the incapability of the environment to disturb the vehicle unsafely [20]. There are three domains: **vehicle security, communications security**, and **edge cloud security** [16].

The AV will interact with the **infrastructure** present in the environment as it drives. We included some key aspects of the transportation infrastructure, such as **sidewalks**, on which pedestrians walk, roads and lanes, on vehicles drive, and traffic signs, which help regulate traffic [18].

It is necessary to create different **navigation models**, as situations require individual treatment tailored to them. Navigating a dirt road through a forest under less than optimal GPS conditions should be treated differently from driving a car in a parking lot [1].

There are three main types of navigation models, such as **global navigation**, where the rest of the system is separate from perception, as there is no need to know which sensors or algorithms were used to create the map; **reactive navigation**, where navigation is directly coupled to perception; and, **guided navigation**, an approach in between global and reactive navigation, because while it does not use metric planning, the resulting motion patterns are not random at all [1].

An AV's **automation level** is defined using a scale of six tiers. **Level 0, no driving automation**, where the driver controls all the mechanical and physical functions of the car, without anything else assuming control. **Level 1, driving assistance**, where the driver operates the vehicle, and the individual control equipment of the vehicle can be controlled by a separate AI agent. **Level 2, partial driving automation**, where the driver is only responsible for part of driving, and the vehicle can handle the rest of the situations. **Level 3, conditional driving automation**, where vehicles can functionally autonomous, but the driver is required to be ready to control the vehicle at all times, in case the system cannot handle a given situation and it is necessary for the driver to take over. **Level 4, high driving automation**, where vehicles can control the vehicle and handle several unexpected situation, but the driver still needs to be aware and alert under special circumstances. Finally, **Level 5, full driving automation**, where vehicles are fully operated by the driving agent and a human agent cannot affect the car [14].

4.2.5 Social Environment Module

In figure 4.5, we represent the relationships in the Social Environment. Most concepts revolve around AV Adoption Factors, from financial concerns to how the product will be consumed, as well as the impact it will have on society. It details, for example, the different business models that can be applied to mobility.

AVs can be differentiated as either **public** or **private vehicles**, concerning who possesses ownership of the vehicle, and as **high occupancy** or **low occupancy**, concerning the capacity of the vehicle - an autonomous bus would be a high occupancy AV.

There are three different kinds of AV **mobility business models**: **Private ownership by individuals**, which would function in the same way as current car ownership, and **private ownership by service providers**, resembling the business model currently used by Uber or Bolt. Both of these use private AVs. The last model is **public ownership by the government**, which would replace public transportation drivers with AI driving agents, and which uses public vehicles. These affect how AVs is adopted into the market, being a financial concern. These business models represent different systems of AV deployment that may be used [21].

When you shine an economic light on the roles one can play in the AV field, we can find the **consumer**. There are several types of consumers, these roles denoting the manner and speed with which people adopt AV technology into the market. Namely, we have **innovators**, the customers who always want to be the first to try the product, and are influenced by mass media; **imitators**, which are influenced by word of mouth [4]; **early adopters** who represent opinion leaders; the **early majority**, who while rarely being leaders, do adopt new ideas before the average population; the **late majority**, customers who are skeptical of change, and wait until most people have tried the product; and, **laggards**, who are bound by tradition and very conservative, rarely trying new products [5].

The introduction of AVs caused profound **social impact**, across several dimensions, among them **public health**, **transportation equity**, as individuals who otherwise would not have easy access to transportation (children, the elderly, the blind) can access increased mobility with the use of AVs [7], and the **environment**, as fuel efficiency is expected to increase [22].

In order for AVs to become a reality, they first must be adopted by the mainstream public, and there are several **factors that impact AV adoption**. Among them are the **consumer's level of education**, as it can impact their pro-technology attitudes [23]. **Environmental determinants** are also a factor, together with media determinants - the information available to the public through **mass** and **social media** impacts the public willingness to use AVs. **Behavioral determinants** and **personal determinants** have a role, as an individual who feels they are capable of traveling with AVs will more easily do so. **Product determinants** also influence AV adoption, either through its **perceived usefulness**, the benefits it provides, or conversely, through its **perceived risks**, the drawbacks it entails [24].

We also found that the **perceived ease-of-use** was a factor, whether from media or from seeing

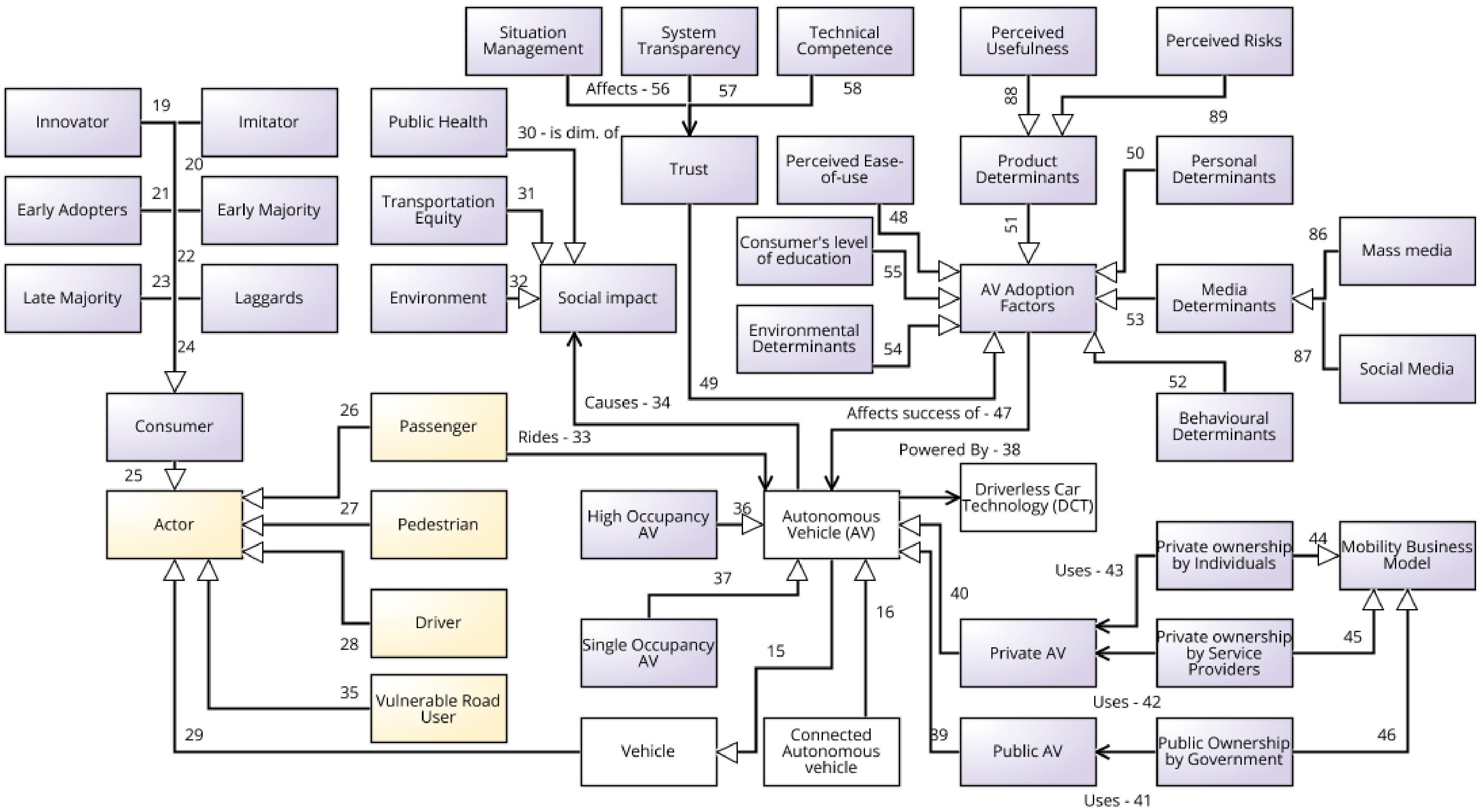

Figure 4.5: Relationship between concepts of the social Environment module.

friends and family use AVs [25]. **Trust** is a big factor as well, as it influences the individual's level of perceived safety. We found three dimensions that influence one's level of trust in AV - **situation management**, **system transparency**, and **technical competence** [9].

In figure 4.6, we detail relationships among the entire domain, using only the core concepts of each of the three modules. This helps understand how the different modules is inter-connected. It also allows a quick overview of the whole scope of the domain.

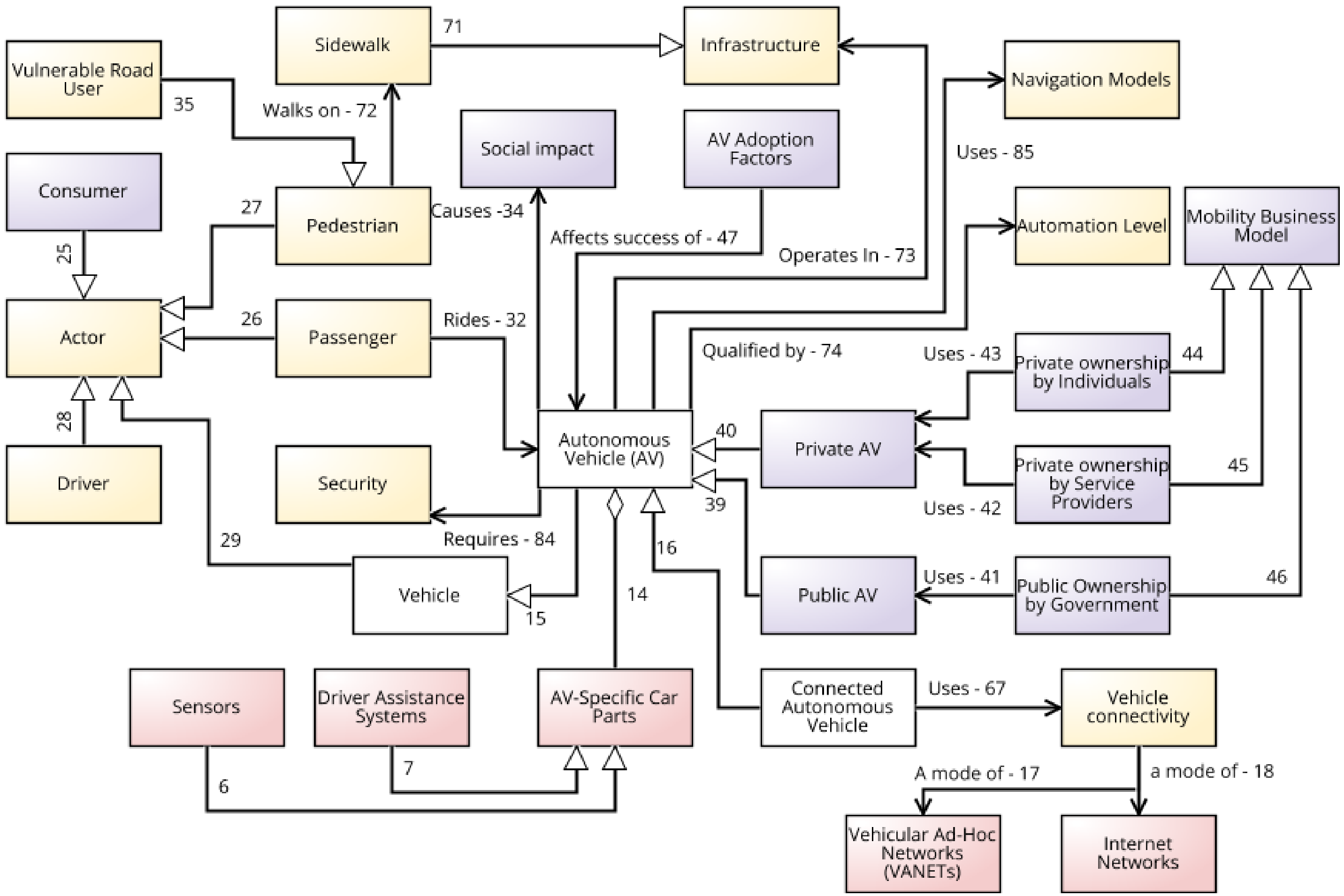

Figure 4.6: Relationship between concepts of all the modules.

5

Evaluate the Ontology

Contents

5.1 Comparing the ontology to the Waymo Experiment

5.1.1 Planning the Review

This SLR was executed to evaluate the thesis, as comparing it to a real-life application of AVs such as the experiment Waymo is conducting in Phoenix, Arizona will show how the ontology compares to an actual instance of AV implementation. The Waymo experiment was selected as it is a complex scenario with many different actors involved, which has been thoroughly covered in the press.

We only establish one research question when planning this review:

Q1: Which concepts in the AV ontology match real-world examples in the Waymo experiment?

We defined the following search string, designed to catch the most relevant documents to our research while filtering out undesirable ones:

(Waymo AND phoenix) OR (Waymo AND (Driverless OR autonomous)) OR (Phoenix AND (Driverless OR autonomous))

We used the following data sources:

- **ACM Digital Library** portal.acm.org
- **EBSCO** ebsco.com/products/ebsco-discovery-service
- **IEEE Digital Library** ieeexplore.ieee.org
- **Scopus** scopus.com

To filter the results obtained, we applied the exclusion and inclusion criteria seen in figure 5.1:

Inclusion Criteria	Exclusion Criteria
Relevant to Waymo experiment in Phoenix	Unable to get full document
Accurate data and information	Not enough scientific credibility
Reputable sources	Not in english
	Out of scope

Figure 5.1: Inclusion and exclusion criteria.

We used these criteria to filter the documents based on their abstracts, and then when reading the documents in full. A final set of documents was then obtained, which provided the information used in this SLR.

We used Parsif.al as the tool to support completing the SLR. To arrive at the final set of documents, we used the same review protocol as in the first SLR we performed, detailed in figure 3.2.

In appendix D we can find the list mapping the final set of documents to identifiers that will be used throughout this SLR when more convenient.

5.1.2 Conducting the Review

In this section we analyze the data obtained, gathering insight and information on the nature of the documents, as well as the evolution that happened until we reached our final set of papers. In figure 5.2 we can see that we initially obtained 491 documents. After removing duplicates we got 323, and after reading the abstracts of these papers obtained a preliminary set of 144. These were then read in full, arriving at the final set of 47 relevant documents.

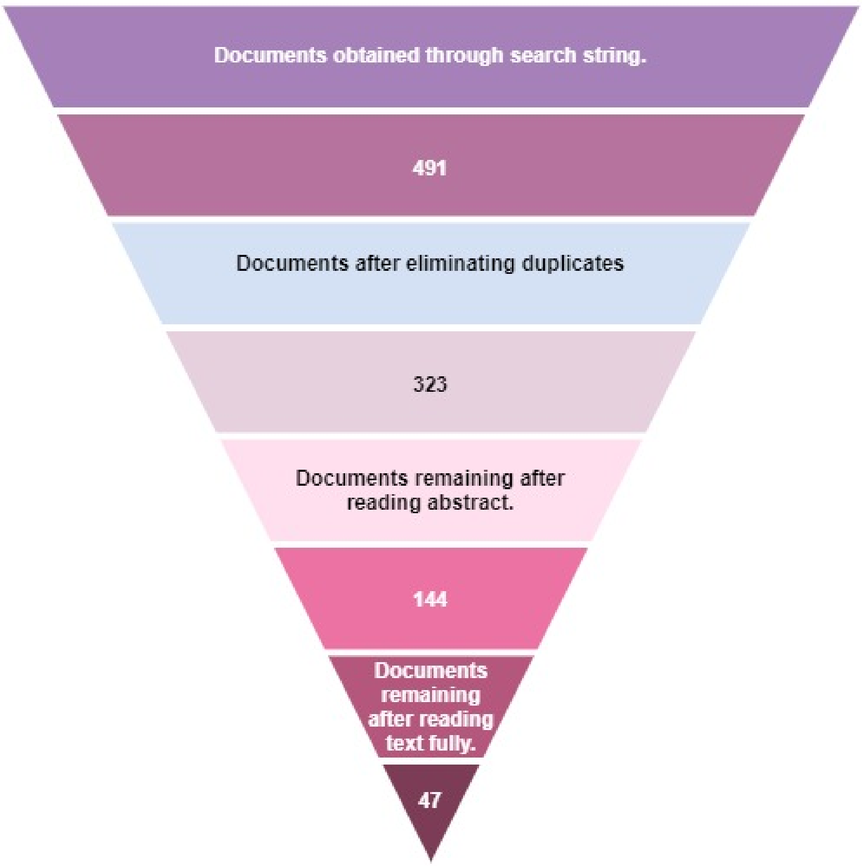

Figure 5.2: Number of documents at each phase.

5.1.2.A Distribution relating to the year of publication

We can see in figure 5.3 that discussion of the Waymo experiment began in 2016, when it was first announced to the public, with most documents being published in 2017 and 2018. More articles were published in 2017 than any other year, which coincides with Waymo's lawsuit against their former employee Anthony Levandowski, which was quite newsworthy. Publication rates tapered off in 2019 and 2020, which is due to interest in the public reducing after the initial reveal, as there was not newsworthy information being reported about the experiment. The COVID-19 pandemic was also a factor, as Waymo was still required to have a safety driver in the vehicle under Arizona regulation during the beginning of the pandemic.

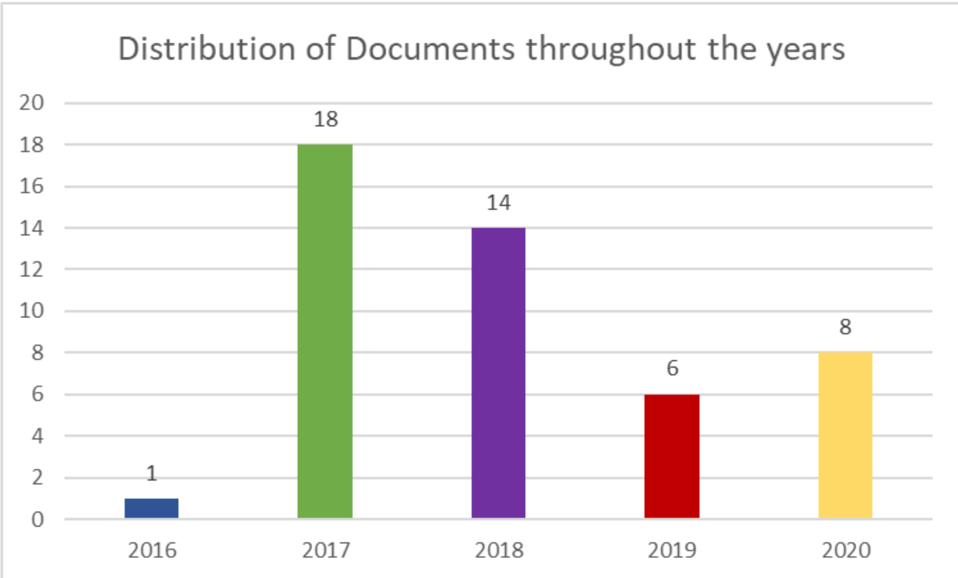

Figure 5.3: Number of documents per year of publication.

5.1.2.B Distribution relating to the type of publication

We can observe in figure 5.4 that the most common type of publication is the periodical, followed closely by the newspaper. This was expected, as the Waymo experiment was a private endeavor where most of the data obtained was not made public. Most of our information came from Waymo's communication with the press, and from press coverage that reported the story to the public.

5.1.3 Reporting the Review

To connect the concepts of our ontology to the instances found in the Waymo experiment, we built the table included in appendix E. This table shows for each concept in the ontology its equivalent in the

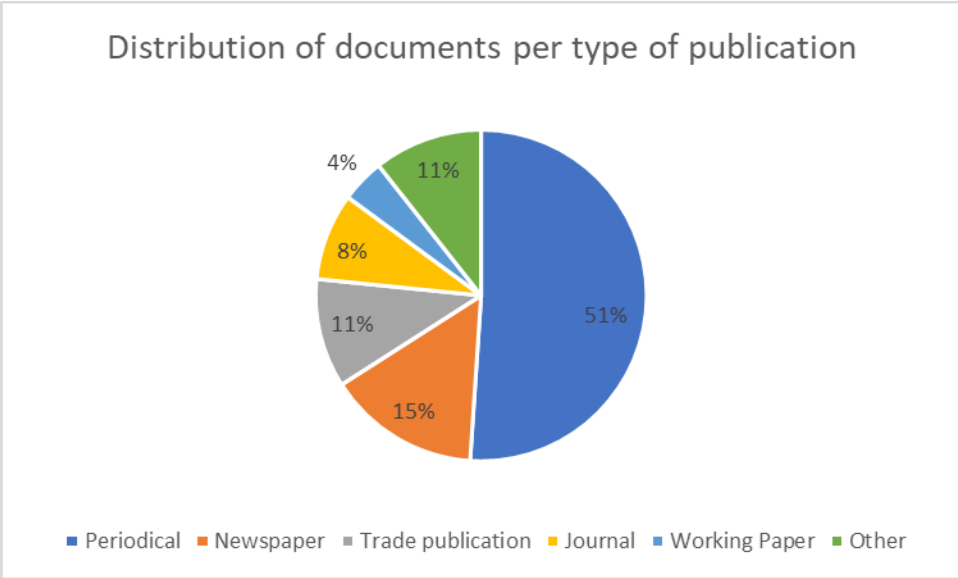

Figure 5.4: Number of documents per type of publication.

Waymo experiment, and quotes from the articles establishing each instance (it is colored pink when there are no matches).

To illustrate the coverage of the concepts mapped, we highlighted the concepts that were found to have equivalents in the Waymo experiment.

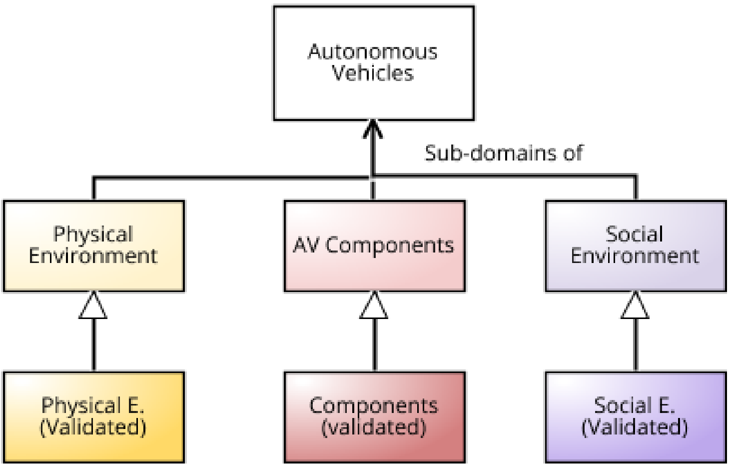

Figure 5.5: Color scheme used to identified the concepts with matches in the Waymo experiment.

In figure 5.5 we identify the colors used to represent matched concepts.

The concepts for which a match was found were colored with a darker shade of the same color attributed to each module in the color scheme determined for the ontology. We also used an asterisk in the concept name to identify matched concepts, used mostly to identify the general concepts, which were colored white.

In figure 5.6 we represent the concepts in the components module.

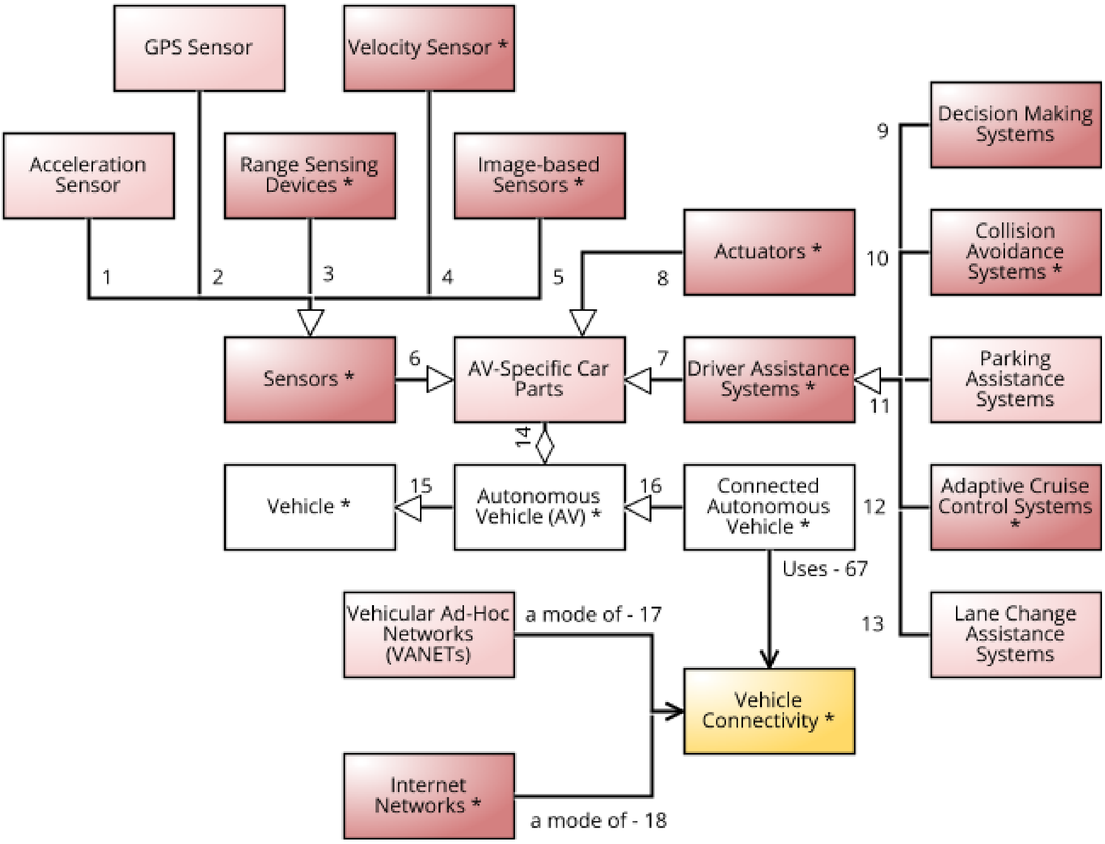

Figure 5.6: Components module with matched concepts highlighted.

In figure 5.7 we represent the concepts in the physical environment module.

And lastly, in figure 5.8 we represent the concepts in the social environment.

5.2 Competency Questions

Competency questions are a tool used in the SABiO methodology to evaluate the ontology. The ontology must be able to answer all the competency questions posed during the requirements elicitation phase. We can find the answers in table 5.1.

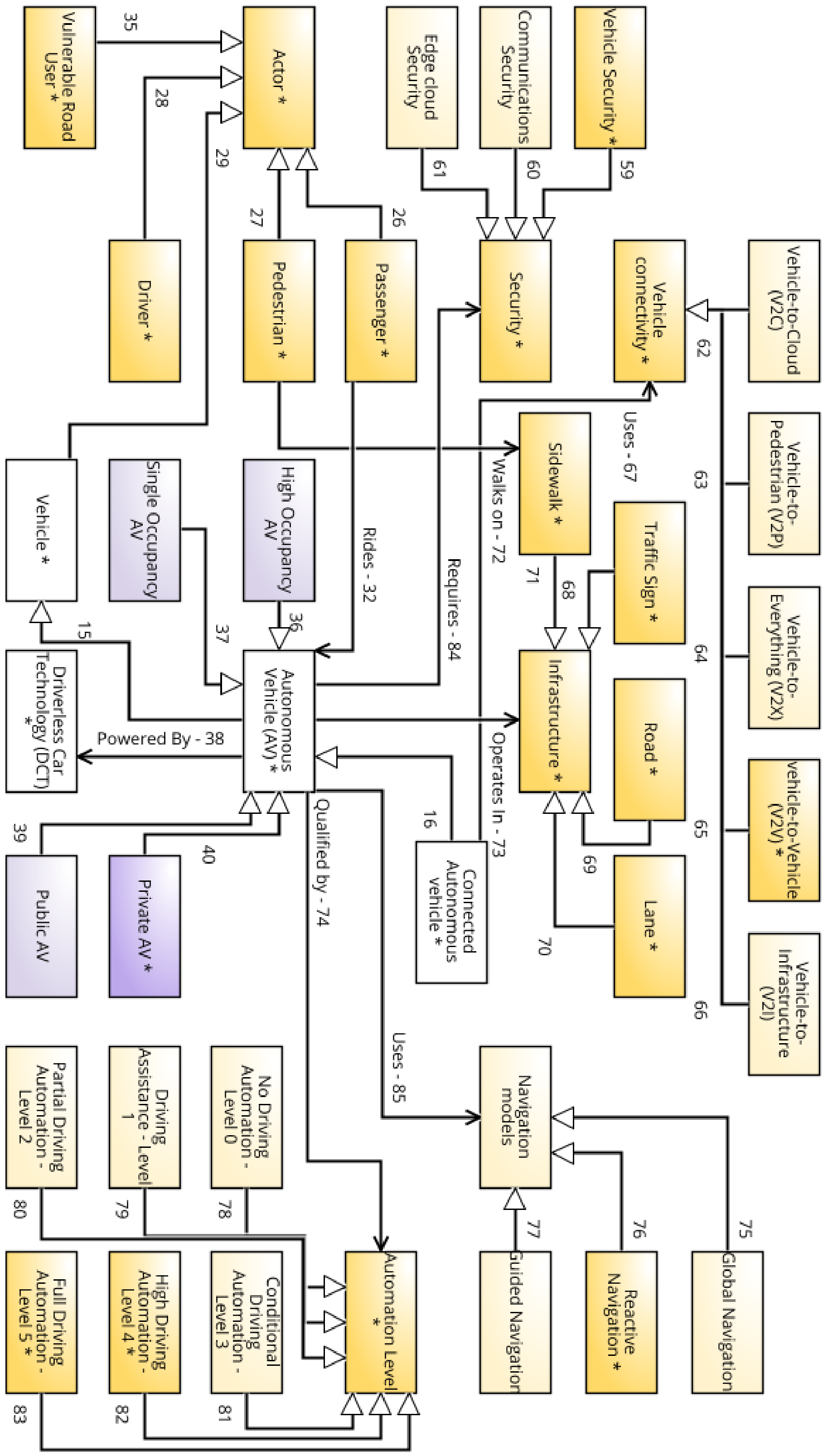

Figure 5.7: Physical environment module with matched concepts highlighted.

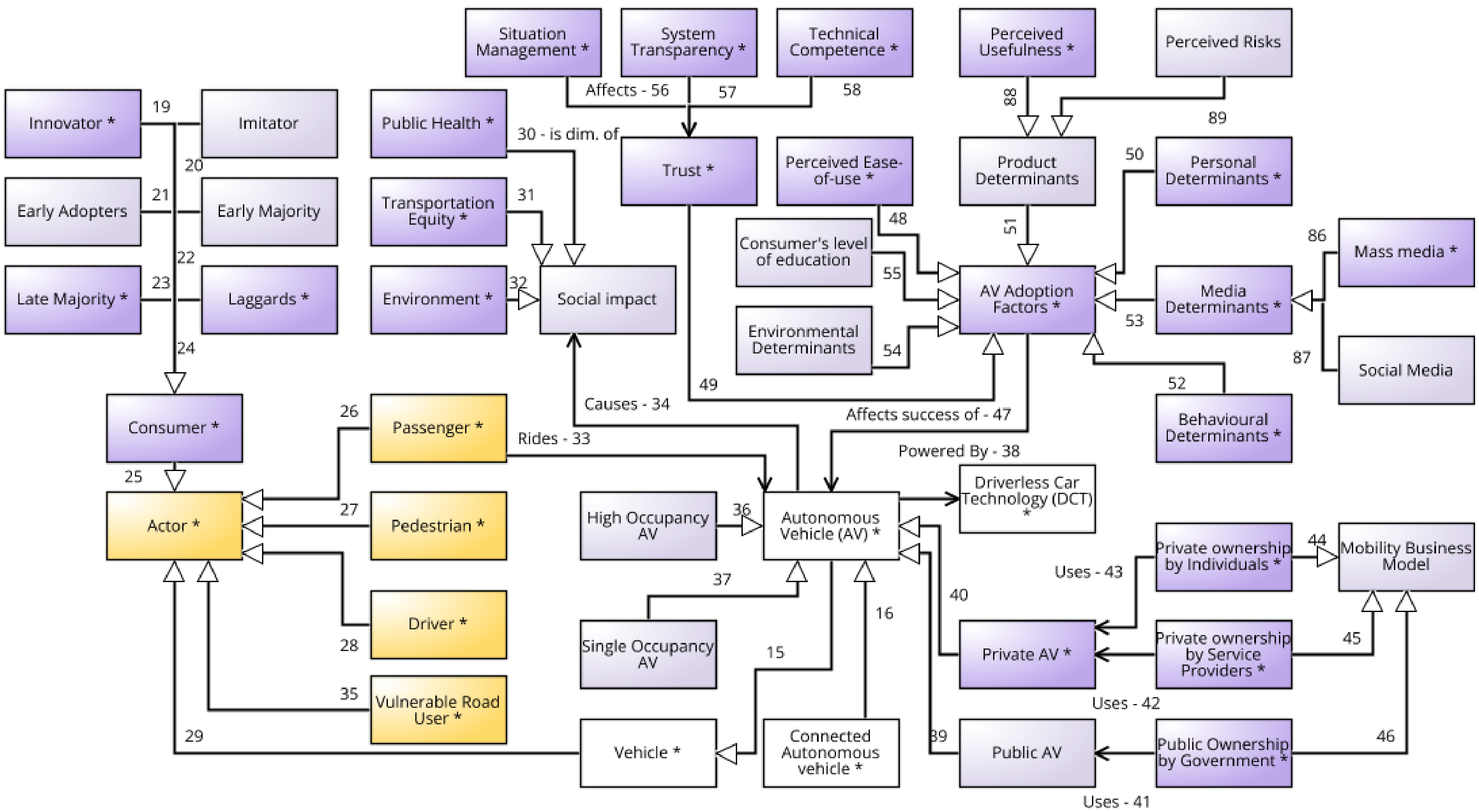

Figure 5.8: Social environment module with matched concepts highlighted.

Table 5.1: Answers to the Competency Questions.

	Competency Question	Answer
CQ1	What influences AV adoption?	AV adoption factors, Behavioural determinants, Consumer's level of education, Environmental determinants, Mass media, Media determinants, Perceived ease-of-use, Perceived risks,Perceived usefulness, Personal determinants, Product determinants, Situation management, Social Media, System transparency, Technical Competence, Trust
CQ2	How can an AV be integrated into society?	Mobility business model, Private ownership by individuals, Private ownership by service providers, Public ownership by government
CQ3	What constitutes the AV's environment?	Infrastructure, Lane, Road, Sidewalk, Traffic sign
CQ4	How does an AV sense its environment?	Acceleration Sensor, GPS Sensor, Image-based sensors, Range sensing devices, Sensors, Velocity sensor
CQ5	How does an AV interact with its environment?	Actuators, Vehicle Connectivity
CQ6	Who are the actors interacting with AVs?	Consumers, Drivers, Passengers, Pedestrians, Vehicles, Vulnerable road users
CQ7	What types of communication do AVs have?	Internet networks, VANETs, V2C, V2I, V2P, V2V, V2X
CQ8	What kinds of AVs exist?	Connected autonomous vehicle, High occupancy AV, Private AV, Public AV, Single occupancy AV

5.3 Discussion

5.3.1 Waymo Experiment SLR

In figures 5.6, 5.7, and 5.8 we can see that the concepts matched to instances in the Waymo experiment cover a good amount of the ontology - to be specific, 58% of concepts were matched. Furthermore, we can see that all general concepts were matched, and we observed that in every hub of concepts a number of them were highlighted, which is a sign of the relevancy of each cluster. For example, in the automation level section, only two concepts were highlighted, but the automation levels used during the experiment are the only ones which would be present in the literature retrieved, and the other levels are proven relevant by the confirmation of the presence of level 4 and level 5. In figure 5.9 we have colored concepts where either 1)the concept was matched or 2) a child concept of the concept in question was matched. For this, we used the schema presented in figure 4.6. We can see virtually all the schema has been highlighted, showing all sections of the ontology have been validated.

5.3.2 Competency Questions.

We can see by the answers to the competency questions that the requirements set for the ontology were met, as it was possible to answer all questions using concepts from the ontology. The concepts used

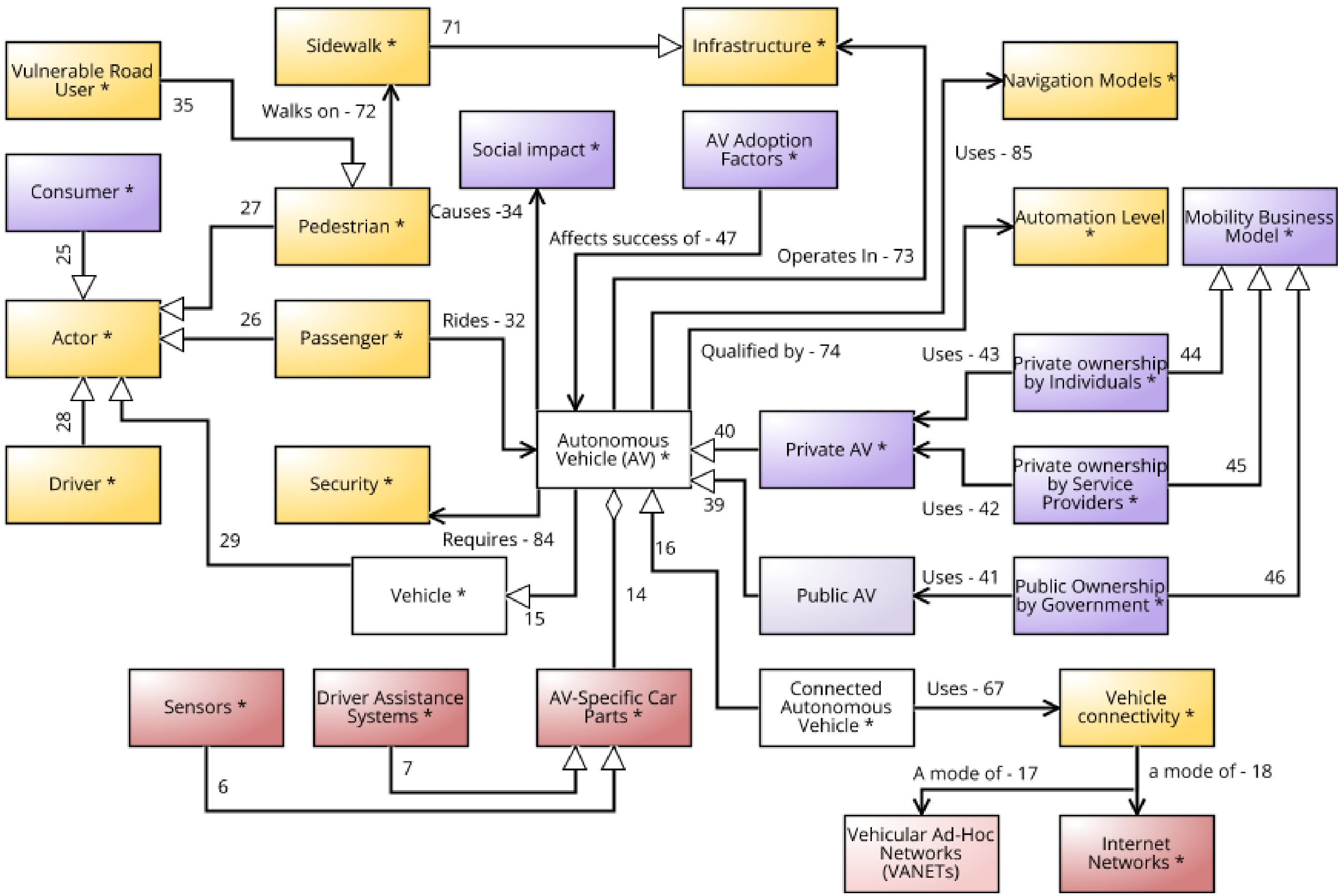

Figure 5.9: Concepts matched in Waymo Experiment SLR.

in the answers originate in all three modules, substantiating the decision to segment the ontology into separate modules.

6

Conclusion

Contents

For this ontology, we used two methodologies - the SABiO methodology and used SLR as a supporting process to SABiO. First, we identified the purpose and all requirements of the ontology, identifying the competency questions that helped us later to verify the ontology.

We divided the ontology into three modules; the first focusing on components and ”parts” of the AV; the second focusing on the physical environment of the vehicle, how it interacts with the environment and the space surrounding it physically; and the last focusing on the social environment, how AV technology interacts with society and how it can impact the general public.

We then performed an SLR to gather all needed data systematically. We obtained a set of concepts, vetted all likely connections, and following the SABiO methodology then arrived at a final ontology.

To evaluate our ontology we used the competency questions defined at the beginning of the development process. We then performed another SLR intending to match the concepts found in our ontology to real-world equivalents pertaining to the application of AV technology happening mainly in the city of Phoenix, by the AV company Waymo, whose parent company is Alphabet. The goal of this SLR is to see if the ontology is consistent with a real-life scenario of AV.

6.1 Contributions

With this ontology, we hope to contribute a resource to both experts on the domain of AV research, as well as governance and city planning officials who have to deal with AV-related matters. Although we found several ontologies on regular unmanned vehicles and their usage, we did not found an ontology focusing specifically on AVs.

6.1.1 Legal/Civil Oversight of AVs

As AVs becomes a reality, there will be a transitional period where government officials and employees will be tasked with implementing guidelines for AV usages, and well as ways to oversee and supervise AV usage, and take vehicle automation into account when it comes to traffic and vehicle regulations. These people may not be professionals in this field, as this will be a worldwide circumstance, and they would benefit from a resource of this nature, which will swiftly inform them of the scope of the concepts that constitute the AV domain.

6.1.2 Information Recovery

There are many researchers working simultaneously in the field of vehicle automation. One of the biggest challenges of research is ensuring all the relevant data and information on the subject has been retrieved. This ontology allows investigators to access a common vocabulary when researching data bases, improving the ability to recover relevant information.

6.2 Limitations

We encountered some obstacles as we conducted this work:

- There are many ways to refer to the same concept, which caused the recovery of the concepts we identified in the literature difficult.
- Most of the information retrieved was focused on a very narrow and technical segment of the AV domain, causing it difficult to find information on, for example, social impact.

6.3 Communication

Intending to communicate the results obtained in this thesis, we submitted an article by the title of ”Autonomous Vehicles - A Conceptual Model” based on this work to the ”Journal of Intelligent Transportation Systems”, a Q1 publication.

This article was based on the SLR we performed as a form of knowledge acquisition for the SABiO methodology in this thesis but did not delve into the SABiO methodology and the whole process of ontology development. While it has been rejected in this first submission, we intend to improve it and resubmit it to a publication relevant to the subject of AVs.

We are also writing an article named ”Autonomous Vehicles - An ontology”, which will detail the SABiO methodology followed here and present the obtained ontology.

6.4 Future Work

The SABiO methodology can be used for the development of reference ontologies, and operational ontologies that build upon the former. These processes are detailed in figure 2.1. We have fulfilled the first two steps, purpose identification and requirements elicitation, and ontology capture and formalization, and obtained a reference ontology.

It would be pertinent to continue the SABiO methodology and create an operational ontology that can be used by computer applications, and complete the design and implementation phases of SABiO. This entails writing it in a particular machine-readable ontology language, such as OWL (web ontology language), paying attention to architectural issues and technological nonfunctional requirements [11].

We would also have benefited from another method of validating the ontology, in order to leave the validation process more complete. For example conducting expert interviews, or another method using domain experts as resources.

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A

Article Identifiers used in the Knowledge Acquisition SLR

Table A.1: Article identifiers for knowledge acquisition SLR.

ID	Article Name	Reference
P1	AV simulation model to assess potential collisions to reduce severity of impacts	[26]
P2	A cellular automaton model considering the exclusive lanes of AV on expressway	[27]
P3	A Semantic Model for Information Sharing in AV Systems	[28]
P4	A solution to ethical and legal problem with the decision-making model of AV	[29]
P5	An effective search and navigation model to an auto-recharging station of driverless vehicles	[30]
P6	An Ontology for Collaborative Navigation among Autonomous Cars, Drivers, and Pedestrians in Smart Cities	[18]
P7	An ontology-based intelligent speed adaptation system for autonomous cars	[31]
P8	An optimal mandatory lane change decision model for AV in urban arterials	[32]
P9	Assessing public perception of self-driving cars The AV acceptance model	[33]
P10	Autonomous ground vehicles-concepts and a path to the future	[1]
P11	AV security: Conceptual model	[16]
P12	Capturing the behavioural determinants behind the adoption of AVs Conceptual frameworks and measurement models to predict public transport, sharing and ownership trends of self-driving cars	[23]
P13	Choice behavior of AV based on logistic models	[14]
P14	Concept Design Optimization of Autonomous and Electric Vehicles	[34]
P15	Conceptual model to explain, predict, & improve user acceptance of driverless podlike vehicles	[9]
P16	Connected traffic data ontology (Ctdo) for intelligent urban traffic systems focused on connected (semi) AV	[35]
P17	Connected, autonomous and electric vehicles The optimum value for a successful business model	[5]
P18	Customer intentions towards AVs in South Africa An extended UTAUT model	[22]
P19	Customer-Relevant Properties of AV Concepts	[20]
P20	Deep learning models for traffic flow prediction in AVs A review, solutions, and challenges	[15]
P21	Deriving metrics of driving comfort for AV A dynamic latent variable model of speed choice	[36]
P22	Ethical and legal dilemma of AV: Study on driving decision-making model under the emergency situations of red light-running behaviors	[17]
P23	Examining the Equity Impacts of AV: A Travel Demand Model Approach	[6]
P24	Factors influencing AV adoption: an application of the technology acceptance model and innovation diffusion theory	[25]
P25	Game theory models for the verification of the collective behaviour of autonomous cars	[37]
P26	Human dynamics based driver model for autonomous car	[38]
P27	Human-like lane change decision model for AV that considers the risk perception of drivers in mixed traffic	[39]
P28	Human-like obstacle avoidance trajectory planning and tracking model for AVs that considers the river's operation characteristics	[40]
P29	Impacts of AV on public health A conceptual model and policy recommendations	[7]

ID	Article Name	Reference
P30	Integrated models of land use and transportation for the AV revolution	[21]
P31	Interface concepts for intent communication from AV to vulnerable road users	[41]
P32	Investigation of the Impacts of Shared AV Operation in Halifax, Canada Using a Dynamic Traffic Microsimulation Model	[42]
P33	Maneuver-based objectification of user comfort affecting aspects of driving style of AV concepts	[43]
P34	Market penetration model for AV on the basis of earlier technology adoption experience	[4]
P35	Measuring Consumer Behavioural Intention to Accept Technology: Towards AV Technology Acceptance Model (AVTAM)	[44]
P36	Model Contrast of AV Impacts on Traffic	[45]
P37	Model of Driving Skills Decrease in the Context of AV	[46]
P38	Model predictive coordination of AV crossing intersections	[47]
P39	Model-predictive planning for AVs anticipating intentions of vulnerable road users by artificial neural networks	[19]
P40	Modelling the acceptance of fully AV A media-based perception and adoption model	[24]
P41	Ontology-Based Driving Scene Modeling, Situation Assessment and Decision Making for AV	[48]
P42	Path planning for AV using model predictive control	[49]
P43	Proof of concept for Scenario-in-the-Loop (SciL) testing for AV technology	[50]
P44	Reputation and Trust Models with Data Quality Metrics for Improving AV Traffic Security and Safety	[51]
P45	Safety concept for AV that operate in pedestrian areas	[52]
P46	Scenario Modeling of AV with Trip-Based Models	[53]
P47	Service-Oriented Cooperation Models and Mechanisms for Heterogeneous Driverless Vehicles at Continuous Static Critical Sections	[54]
P48	The travel and environmental implications of shared AV, using agent-based model scenarios	[8]
P49	Toward Implementing the ADC Model of Moral Judgment in AV	[55]
P50	Towards Efficient Hazard Identification in the Concept Phase of Driverless Vehicle Development.	[56]
P51	Trust dynamics in human AV interaction A review of trust models	[57]
P52	Utilizing Technology Acceptance Model (TAM) for driverless car technology.	[58]

B

Contribution of Knowledge Acquisition Articles to each Module

Table B.1: Relevancy of each article to the modules.

ID	Components	Social Environment	Physical Environment
P1	○	○	●
P2	○	●	○
P3	◐	○	●
P4	●	●	○
P5	○	○	●
P6	○	○	●
P7	◐	○	●
P8	○	○	●
P9	○	●	○
P10	●	○	●

ID	Components	Social Environment	Physical Environment
P11	●	○	○
P12	○	●	○
P13	○	○	●
P14	○	●	●
P15	○	●	○
P16	●	○	◐
P17	○	●	◐
P18	○	●	○
P19	○	●	◐
P20	●	◐	◐
P21	○	●	●
P22	●	◐	○
P23	○	●	◐
P24	○	●	○
P25	○	○	●
P26	○	◐	●
P27	●	○	●
P28	◐	○	●
P29	○	●	○
P30	○	●	○
P31	○	○	●
P32	○	○	●
P33	○	●	◐
P34	○	●	○
P35	○	●	○
P36	○	●	○
P37	○	○	●
P38	●	○	◐
P39	○	○	●
P40	○	●	○
P41	○	○	●
P42	○	○	●
P43	○	●	○
P44	●	○	○
P45	●	◐	◐
P46	○	●	○
P47	○	○	●
P48	○	●	◐
P49	○	●	○
P50	○	●	◐
P51	○	●	◐
P52	●	●	○

Table B.2: Key for the symbols used.

Symbol	Meaning
●	Relevant
◐	Partially Relevant
○	Not Relevant

C

Validation of Connections between Concepts

Table C.1: Connections between concepts.

ID	First Concept	Second Concept	Relationship Type	Sources
C1	Sensors	Acceleration Sensor	Generalization	P16
C2	Sensors	GPS Sensor	Generalization	P16
				P7
C3	Sensors	Range Sensing Devices	Generalization	P10
				P7
C4	Sensors	Velocity Sensor	Generalization	P16
C5	Sensors	Image-based Sensors	Generalization	P10
				P7
C6	AV-Specific car parts	Sensors	Generalization	P16
				P11
				P10
				P7
				P13
				P20
				P3
C7	AV-Specific car parts	Driver Assistance Systems	Generalization	P52
				P4
				P10
				P27
C8	AV-Specific car parts	Actuators	Generalization	P16
				P11
				P10
				P13
				P20
				P3
C9	Driver Assistance Systems	Decision Making Systems	Generalization	P4
				P22
C10	Driver Assistance Systems	Collision Avoidance Systems	Generalization	P52
				P28
C11	Driver Assistance Systems	Parking Assistance Systems	Generalization	P52
C12	Driver Assistance Systems	Adaptive Cruise Control Systems	Generalization	P52
				P10
				P27
c13	Driver Assistance Systems	Lane Change Systems	Generalization	P52
				P10
				P27
C14	Autonomous Vehicle (AV)	AV-Specific car parts	Aggregation	P11
				P10
C15	Autonomous Vehicle (AV)	Vehicle	Generalization	P6
				P41
				P17
C16	Autonomous Vehicle (AV)	Connected Autonomous Vehicle	Generalization	P16
				P13
				P17
C17	Vehicle Connectivity	Vehicular Ad-Hoc Networks (VANETs)	A mode of	P11
				P44
				P20

ID	First Concept	Second Concept	Relationship Type	Sources
C18	Vehicle Connectivity	Internet Networks	A mode of	P11
C19	Innovator	Consumer	Generalization	P34 P17
C20	Imitator	Consumer	Generalization	P34
C21	Early Adopters	Consumer	Generalization	P17
C22	Early Majority	Consumer	Generalization	P17
C23	Late Majority	Consumer	Generalization	P17
C24	Laggards	Consumer	Generalization	P17
C25	Consumer	Actor	Generalization	P17
C26	Passenger	Actor	Generalization	P15 P19 P45
C27	Pedestrian	Actor	Generalization	P6 P41
C28	Driver	Actor	Generalization	P6 P19
C29	Vehicle	Actor	Generalization	P6
C30	Social Impact	Public Health	Is a dimension of	P29
C31	Social Impact	Transportation Equity	Is a dimension of	P23 P15 P29
C32	Social Impact	Environment	Is a dimension of	P29 P40 P18
C33	Autonomous Vehicle (AV)	Passenger	Rides	P19
C34	Autonomous Vehicle (AV)	Social Impact	Causes	P52 P40
C35	Actor	Vulnerable Road user	Generalization	P39 P31
C36	Autonomous Vehicle (AV)	High Occupancy AV	Generalization	P23
C37	Autonomous Vehicle (AV)	Single Occupancy AV	Generalization	P23
C38	Autonomous Vehicle (AV)	Driverless Car Technology	Powered By	P52 P23
C39	Autonomous Vehicle (AV)	Public AV	Generalization	P6 P46
C40	Autonomous Vehicle (AV)	Private AV	Generalization	P6 P46
C41	Public AV	Public ownership by government	Uses	P12 P30
C42	Private AV	Private Ownership by Service Providers	Uses	P48 P12 P30
C43	Private AV	Private Ownership by Individuals	Uses	P48 P12 P30
C44	Private Ownership by Individuals	Mobility Business Model	Generalization	P48 P12 P30

ID	First Concept	Second Concept	Relationship Type	Sources
C45	Private Ownership by Service Providers	Mobility Business Model	Generalization	P48 P12 P30
C46	Public ownership by government	Mobility Business Model	Generalization	P12 P30
C47	Autonomous Vehicle (AV)	AV Adoption Factors	Affects success of	P52 P15 P40 P18 P24 P51
C48	AV Adoption Factors	Perceived Ease of Use	Generalization	P52 P24 P12
C49	AV Adoption Factors	Trust	Generalization	P15 P24 P51
C50	AV Adoption Factors	Personal Determinants	Generalization	P40
C51	AV Adoption Factors	Product Determinants	Generalization	P40
C52	AV Adoption Factors	Behavioural Determinants	Generalization	P40
C53	AV Adoption Factors	Media Determinants	Generalization	P40
C54	AV Adoption Factors	Environmental Determinants	Generalization	P40 P18
C55	AV Adoption Factors	Consumer’s level of education	Generalization	P12
C56	Trust	Situation Management	Affects	P15
C57	Trust	System Transparency	Affects	P15
C58	Trust	Technical Competence	Affects	P15
C59	Security	Vehicle Security	Generalization	P11
C60	Security	Communications Security	Generalization	P11
C61	Security	Edge Cloud Security	Generalization	P11
C62	Vehicle Connectivity	V2C	Generalization	P17
C63	Vehicle Connectivity	V2P	Generalization	P17
C64	Vehicle Connectivity	V2X	Generalization	P17
C65	Vehicle Connectivity	V2V	Generalization	P38 P47 P17
C66	Vehicle Connectivity	V2I	Generalization	P47 P17
C67	Connected Autonomous Vehicle	Vehicle Connectivity	Uses	P17 P11 P44 P20
C68	Infrastructure	Traffic Sign	Generalization	P6 P41
C69	Infrastructure	Road	Generalization	P6 P16 P41 P7

ID	First Concept	Second Concept	Relationship Type	Sources
C70	Infrastructure	Lane	Generalization	P6 P41 P7
C71	Infrastructure	Sidewalk	Generalization	P6 P41
C72	Pedestrian	Sidewalk	Walks On	P6
C73	Autonomous Vehicle (AV)	Infrastructure	Operates in	P6
C74	Autonomous Vehicle (AV)	Automation Level	Qualified By	P13
C75	Navigation Model	Global Navigation	Generalization	P10
C76	Navigation Model	Reactive Navigation	Generalization	P10
C77	Navigation Model	Guided Navigation	Generalization	P10
C78	Automation Level	Level 0	Generalization	P13
C79	Automation Level	Level 1	Generalization	P13
C80	Automation Level	Level 2	Generalization	P13
C81	Automation Level	Level 3	Generalization	P13
C82	Automation Level	Level 4	Generalization	P13
C83	Automation Level	Level 5	Generalization	P13
C84	Autonomous Vehicle (AV)	Security	Requires	P11 P19 P29 P45
C85	Autonomous Vehicle (AV)	Navigation Model	Uses	P10
C86	Media Determinants	Mass media	Generalization	P40
C87	Media Determinants	Social Media	Generalization	P40
C88	Product Determinants	Perceived usefulness	Generalization	P52 P40 P18 P24 P12
C89	Product Determinants	Perceived risks	Generalization	P40

D

Article Identifiers used in the Waymo Experiment SLR

Table D.1: Article identifiers for Waymo experiment SLR.

ID	Article Name	Reference
W1	A Huge Moment for Driverless Cars.	[59]
W2	Afraid To Get In Waymo's Driverless Car? A New Insurance Company Has You Covered.	[60]
W3	Alphabet s self driving cars to get their first real riders.	[61]
W4	Alphabet's Waymo Adds Semi-Trucks To Its Driverless Vehicle Portfolio.	[62]
W5	Alphabet's Waymo Raises $2.25 Billion For Driverless Cars.	[63]
W6	Alphabet's Waymo Takes on Freight in Atlanta Driverless Semis.	[64]
W7	Alphabet's Waymo Teams Up With Lyft to Test Autonomous Cars (1).	[65]
W8	Alphabet's Waymo to launch driverless taxi service.	[66]
W9	AutoNation Celebrates Waymo Riders in Arizona.	[67]
W10	Autonomous Cars: Why General Motors Is In The Back Seat Vs. Waymo.	[68]
W11	AV company Waymo to test in Florida rain.	[69]

ID	Article Name	Reference
W12	AVs are cost-effective when used as taxis	[70]
W13	California Permits Waymo to Test Driverless Autonomous Cars on Its Streets.	[71]
W14	Can Google's Waymo Steer Clear Of Uber, Tesla Self-Driving Car Woes?.	[72]
W15	Chandler employees to use self-driving cars for work rides.	[73]
W16	Clash Of The Autonomous Titans: Alphabet's Waymo Sues Uber Claiming Tech Theft.	[74]
W17	Daimler and Waymo to develop autonomous Class 8 trucks.	[75]
W18	Daimler Trucks and Waymo partner on development of autonomous SAE Level 4 trucks.	[76]
W19	Waymo is giving hundreds of people access to their own self-driving cars	[77]
W20	Groupe Renault, Waymo and the Paris Region are exploring setting up an autonomous mobility service between Roissy-Charles De Gaulle and La Defense.	[78]
W21	How Google Can Race Ahead Of The Pack In Self-Driving Cars.	[79]
W22	How Waymo Is Working to Bring Driverless Car to the World's Highways.	[80]
W23	Inside the life of waymo's driverless test family.	[81]
W24	Is the Law Ready for Driverless Cars?	[82]
W25	No Hands, Full Speed Ahead.	[83]
W26	Perceptions of safety on a shared road: Driving, cycling, or walking near an AV	[84]
W27	Scalability in perception for autonomous driving: Waymo open dataset	[85]
W28	SELF-DRIVING CAR SHUTTLES TESTED.	[86]
W29	Self-Driving Cars: Why 2018 Will Be The Year The Rubber Hits The Road.	[87]
W30	Strategic Analysis of Waymo's Future Autonomous Disruptive Capabilities for the Automotive Industry - Research and Markets.	[88]
W31	The Driverless Car and the Legal System: Hopes and Fears as the Courts, Regulatory Agencies, Waymo, Tesla, and Uber Deal with this Exciting and Terrifying New Technology.	[89]
W32	The Flexible City.	[90]
W33	Uber's Driverless Car Ambitions at Stake in Waymo Court Clash.	[91]
W34	WAY TO GO: The first solo passenger of Google's autonomous Waymo vehicle spoke to OT about returning mobility to the blind.	[92]
W35	Waymo Buys 'Thousands' More Chrysler Vans for Driverless Service.	[93]
W36	Waymo chief on driverless car IP: 'Prepare for all outcomes'.	[94]
W37	Waymo Could Be Google Stock Catalyst As Phoenix Launch Nears.	[95]
W38	Waymo Drops 3 Claims in Suit Against Uber on Driverless Cars.	[96]
W39	Waymo first to test fully driverless cars as it focuses on 'shared mobility' future.	[97]
W40	Waymo is first to ditch drivers: AVs go hands-free in Arizona suburb.	[97]
W41	Waymo Is Millions Of Miles Ahead In Robot Car Tests; Does It Need A Billion More?.	[98]
W42	Waymo is Poised to Become Largest Autonomous Technology Company in the Automotive Industry by 2030.	[99]
W43	Waymo opens fully driverless service to general public in Phoenix.	[100]
W44	Waymo Public Road Safety Performance Data.	[101]
W45	Waymo rolls out autonomous vans without human drivers.	[102]
W46	Waymo s next challenge making driverless passengers feels safe.	[103]
W47	Waymo tests hardware to ease passenger fears of driverless cars.	[104]

E

Matching the ontology concepts to instances found in the Waymo Experiment

Table E.1: Matching ontology concepts to Waymo experiment.

ID	Concept	Sub-domain	Article	Equivalent concept
M1	Autonomous Vehicle (AV)	General Concepts	W1	*Driverless Car, Autonomous Vehicle*
			W3	*Autonomous car*
			W9	*Self driving vehicles*
M2	Connected Autonomous Vehicle	General Concepts	W30	*Connected and autonomous vehicle*
			W42	*Connected devices*
M3	Driverless Car Technology (DCT)	General Concepts	W5	*Autonomous driving technology*
			W7	*Self driving technology*
			W42	*Autonomous technology*
M4	Vehicle	General Concepts	W1	*Chrysler Pacifica Minivans*
			W3	*Chrysler Pacifica Minivans*
			W35	*Vehicles*
M5	Acceleration Sensor	Components		
M6	Actuators	Components	W45	*Braking and steering systems*
M7	Adaptive Cruise Control Systems	Components	W31	*Adaptive Cruise Control*
M8	AV-Specific car parts	Components		
M9	Collision Avoidance Systems	Components	W12	*Microsimulation modeling of future crashes*
			W22	*Software*
M10	Decision Making Systems	Components	W14	*AI software programs that aim to make decisions*
M11	Driver Assistance Systems	Components	W2	*Software*
			W4	*Software*
			W6	*Self drive system*
			W14	*AI software*
			W26	*Driver assistance systems*
			W37	*Advanced software algorithms*
M12	GPS Sensor	Components		
M13	Image-based Sensors	Components	W14	*cameras*
			W16	*Cameras*
			W27	*Cameras*
M14	Internet Networks	Components	W32	*Internet*
M15	Lane Change Assistance Systems	Components		
M16	Parking Assistance Systems	Components		
M17	Range Sensing Devices	Components	W11	*Radar sensors*
			W14	*Radar*
			W16	*LIDAR*
			W27	*LIDAR*
			W33	*LIDAR*
			W38	*LIDAR*
			W39	*Radar*
M18	Sensors	Components	W2	*Sensors*
			W6	*Sensors*
			W14	*Laser beam scanning, radar, cameras*
			W16	*Sensors*

ID	Concept	Sub-domain	Article	Equivalent concept
M19	Vehicular Ad-Hoc Networks (VANETs)	Components		
M20	Velocity Sensor	Components	W14	*radar for measuring velocity*
M21	Actor	Physical Environment	W26	*Potencial roles*
M22	Automation Level	Physical Environment	W26	*Level of automation*
M23	Communications Security	Physical Environment		
M24	Driver	Physical Environment	W1	*Driver*
			W4	*Driver*
			W6	*Driver*
			W8	*Driver*
M25	Edge Cloud Security	Physical Environment		
M26	Global Navigation	Physical Environment		
M27	Guided Navigation	Physical Environment		
M28	Infrastructure	Physical Environment	W20	*Infrastructure*
M29	Lane	Physical Environment	W22	*Lane*
M30	Level 0	Physical Environment		
M31	Level 1	Physical Environment		
M32	Level 2	Physical Environment		
M33	Level 3	Physical Environment		
M34	Level 4	Physical Environment	W12	*Level 4*
			W14	*Level 4*
			W16	*Level 4*
			W17	*Level 4*
			W39	*Level 4*
M35	Level 5	Physical Environment	W13	*[No] test driver in the car*
			W25	*Without a human driver*
			W42	*Level 5*
M36	Navigation Model	Physical Environment		
M37	Passenger	Physical Environment	W1	*Passenger*
M38	Path	Physical Environment		
M39	Pedestrian	Physical Environment	W2	*Pedestrian*
M40	Reactive Navigation	Physical Environment	W22	*(...) determine what's on the road and react accordingly*
			W45	*instantly diagnose any problems and [act]*
M41	Road	Physical Environment	W14	*road*
			W29	*Road*
M42	Security	Physical Environment	W26	*Cybersecurity*
			W36	*Safety*
M43	Sidewalk	Physical Environment	W27	*Sidewalks*
			W32	*Sidewalks*
M44	Traffic Sign	Physical Environment	W14	*Traffic lights and stop signs*
M45	V2C	Physical Environment		
M46	V2I	Physical Environment		
M47	V2P	Physical Environment		
M48	V2V	Physical Environment	W31	*Vehicle-to-vehicle*
M49	V2X	Physical Environment		
M50	Vehicle Connectivity	Physical Environment	W24	*Connectivity*
			W42	*Connectivity*
M51	Vehicle Security	Physical Environment	W26	*Vehicle failure as a threat*

ID	Concept	Sub-domain	Article	Equivalent concept
M52	Vulnerable road user	Physical Environment	W21	*pedestrian [killed by crash]*
			W26	*Vulnerable road user*
M53	AV Adoption Factors	Social Environment	W26	*Acceptance of AVs*
M54	Behavioural Determinants	Social Environment	W26	*Behavioural intention to ride in AVs*
M55	Consumer	Social Environment	W14	*Consumer*
			W28	*Consumer*
M56	Consumer's level of education	Social Environment		
M57	Early Adopters	Social Environment		
M58	Early Majority	Social Environment		
M59	Environment	Social Environment	W15	*Reduced vehicle fleet*
			W40	*Reduced greenhouse emissions*
M60	Environmental Determinants	Social Environment		
M61	High Occupancy AV	Social Environment		
M62	Imitator	Social Environment		
M63	Innovator	Social Environment	W1	*Early rider*
			W2	*Early rider*
			W3	*Early rider*
			W9	*Early rider*
			W26	*Pioneers*
M64	Laggards	Social Environment	W2	*Respondents indicated they were not ready to take a a ride in an AV*
			W26	*Laggards*
M65	Late Majority	Social Environment	W19	*Many skeptical people*
M66	Mass media	Social Environment	W26	*News*
M67	Media Determinants	Social Environment	W26	*News*
M68	Mobility Business Model	Social Environment		
M69	Perceived Ease of Use	Social Environment	W2	*painless journey, peace of mind*
M70	Perceived risks	Social Environment		
M71	Perceived usefulness	Social Environment	W40	*Reduced transportation costs*
M72	Personal Determinants	Social Environment	W3	*NA*
			W26	*Subjective norms*
M73	Private AV	Social Environment	W1	*its Chrysler Pacifica Minivans*
			W3	*Its fleet*
			W41	*Its fleet*
			W43	*fully-owned fleet*
M74	Private Ownership by Individuals	Social Environment	W3	*Personal car ownership*
			W23	*Personal vehicle*
M75	Private Ownership by Service Providers	Social Environment	W2	*Smartphone App, Commercial ride service, Ride sharing*
			W3	*Ride sharing firms*
			W7	*Ride hailing service*
			W8	*Ride hailing service*
			W10	*Ride hailing service*

ID	Concept	Sub-domain	Article	Equivalent concept
M76	Product Determinants	Social Environment		
M77	Public AV	Social Environment		
M78	Public Health	Social Environment	W40	*Increased urban land*
M79	Public ownership by government	Social Environment	W23	*Public transportation*
M80	Single Occupancy AV	Social Environment		
M81	Situation Management	Social Environment	W41	*Handle anything*
M82	Social Impact	Social Environment		
M83	Social Media	Social Environment		
M84	System Transparency	Social Environment	W47	*Car telling passengers what it's doing*
M85	Technical Competence	Social Environment	W26	*Technical error as a concern*
			W46	*Confidence the car is competent*
M86	Transportation Equity	Social Environment	W3	*signing up hundreds of people with diverse backgrounds and transportation needs*
			W19	*teen drivers seeking independence on the road*
			W23	*Pickups for people with disabilities*
			W25	*Retirees and the disabled*
			W34	*Mobility to the blind*
			W44	*Improve mobility for all*
M87	Trust	Social Environment	W21	*Trust*
			W23	*Trust*
			W41	*Reliability*