Autonomous Vehicles Ontology

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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.

Additional Key Words and Phrases: Ontology; Autonomous; Driverless; Vehicles; Cars; Concepts; Model

ACM Reference Format:
Cecilia Baltazar, Miguel Leitão Bignolas Mira da Silva, and Flavia Maria Santoro. 2021. Autonomous Vehicles Ontology. 1, 1 (July 2021), 8 pages. https://doi.org/10.1145/nnnnnnn.nnnnnnn

1 INTRODUCTION

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. Globally, vehicle automation is a sector that has been growing steadily over time. Nowadays the crucial factor in vehicle automation is consumer adoption, and how readily the general public accepts AV as a reality. Automotive companies would benefit from knowing which factors influence autonomous vehicles' (AV) adoption by the public [Koul and Eydgahi 2018].

Consumer adoption is not, however, the only factor for success for AV. For example, in order 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 road operators need to have detailed and current knowledge of the vehicles [Ehrlich et al. 2016]. While AVs can be programmed to communicate with other elements and actors in its environment, they are capable of operating by gathering information about their surroundings using sensors [Lavasani et al. 2016].

Given the success of and the interest in the field of AV, investigation in this subject has been growing exponentially over the years. With many researchers working on the topic, it would be useful to have a way to provide a common understanding and vocabulary to them, allowing them, for example, to find each other's works on the subject more efficiently, and to then build upon one another's work. With this goal, we propose to create an ontology for autonomous vehicles, finding and organizing concepts from its entire domain. In order to do this, we employed the SABiO methodology [Falbo 2014], and used the systematic literature review [Kitchenham 2007] to support one of its processes.

We present these methodologies in Section 2. In Section 3 and 4, we describe the process of the ontology construction. In Section 5 we evaluate the ontology. Finally, in Section 6, we discuss our results and conclude the paper.

2 METHODOLOGY

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 [Noy and McGuinness 2001].

In order 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 [Falbo 2014], and is a method for building ontologies, specifically for the development of domain reference ontologies. A domain ontology is built with the goal of making the best possible description of the domain. 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.
- **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).

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XXXX-XXXX/2021/7-ART $15.00
https://doi.org/10.1145/nnnnnnn.nnnnnnn

- **Implementation;** Regards implementing the ontology in the chosen operational language.
- **Test;** In this phase we must verify and validate the behaviour of the operational ontology.

In order 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. In this thesis we will be producing a reference ontology, and will execute the first two activities.

One of SABiO's supporting processes is the knowledge acquisition. In order to accomplish the knowledge acquisition, we performed a Systematic Literature Review to obtain the relevant studies and extract the necessary terms and relations between said terms.

2.2 Systematic Literature Review

Systematic literature review (SLR) is a research methodology that has been commonly used in the fields of medicine and science. It is a form of secondary study, which reviews all primary studies (empirical studies investigating a specific research question) connected to a specific research question to integrate evidence related to said specific research question.

An SLR comprises three phases: planning the review, conducting the review, and reporting the review:

- **Planning the review** In this phase the need for the review in the first place must be confirmed, the research questions must be defined, and a review protocol defining the basic review procedures must be produced.
- **Conducting the review** consists of finding as many primary studies as possible using an unbiased search strategy. Inclusion and exclusion criteria which address the quality of the studies in question should be defined and applied to the studies obtained. Finally, data should be extracted and all the information necessary to address the research questions must be collected.
- When **reporting the review**, the data collected must be integrated and synthesized to answer the research questions, then presenting the results.

A SLR identifies, analyzes and interprets 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, in order to apply it to computer science research [Kitchenham 2007].

These guidelines allow researchers to accomplish several goals. One can summarize existing evidence concerning a given subject, provide a framework to plan new research activities appropriately, and identify any 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.

3 PURPOSE IDENTIFICATION AND REQUIREMENTS ELICITATION

This 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. For this paper, 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 (CQs), using a middle out strategy (writing down important questions that can then be classified into abstract and simple questions). The following CQs were obtained:

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

The last step is to identify if there is a need for modularization, which consists of defining models modules that can be considered separately while still being connected to other modules. The domain for this ontology is quite vast, and therefore we decided to separate 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 ONTOLOGY CAPTURE AND FORMALIZATION

The second phase of the SABiO methodology is the capture and formalization of the concepts and relations in the domain, and they must be identified and organized. A graphical model should then be designed, as it helps support communication and to establish consensus when delineating the ontology. This phase is strongly supported by the knowledge acquisition process. In order to complete this task, we performed a Systematic Literature Review.

4.1 Planning the Review

Our goal when performing this SLR is to systematically discover, read, and analyze documents relevant to our domain - autonomous vehicles. In order to do this we designed our review protocol. First we defined the research questions:

- **RQ 1:** What are the main concepts related to AVs?
- **RQ 2:** What are the relationships between them?

We used the following search string: ("Model" OR "Representation" OR "Ontology" OR "Concept") AND ("Autonomous" OR "Driverless" OR "Self-driving") AND ("Vehicle" OR "Car"), and we used the following data sources: ACM Digital Library, EBSCO, IEEE Digital Library, and Scopus.

These are our inclusion criteria:

- Concerning terrestrial AVs with the goal of passenger transport

- Key to discussing the topic (i.e. important for defining the domain)
- Relevant to the field of AV
- not general to the domain of Vehicles in general

And these are our exclusion criteria:

- Published before 2012
- Without scientific credibility
- Not in english
- Out of scope
- Purely technical
- Unable to get full document

4.2 Conducting the Review

After executing our research protocol, we obtained a set of 1346 documents. After eliminating duplicate articles, we had 499. We then read all abstracts for these papers and selected a final set of 151 documents, which were all read in full. We reached a final set of 52 papers which were relevant to our research.

After analyzing these 52 papers, we realized that most of the papers were written recently, with the number of papers written rising each year, and the majority being written in 2018. This shows us that interest in this field has risen consistently over the years.

We also found that some publication provided multiple papers in our final set. However, most publications account only for one paper. This shows us that research in the AV area comes from various sources and types of publications, with different areas of focus and investigation.

4.3 Reporting the Review

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 [Koul and Eydgahi 2018] 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 [Toglaw et al. 2018] it is referred to as an AV that is equipped with Internet access, and 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" [Miglani and Kumar 2019].

4.3.1 Components Module. In figure 1, we detail the relationships in the Components module.

4.3.2 Physical Environment Module. In figure 2, 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.

4.3.3 Social Environment Module. In figure 3, 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.

5 EVALUATION - WAYMO EXPERIMENT

In order to evaluate this ontology, we used a real-life application of AV technology - the experiment conducted by Waymo in Phoenix, Arizona.

5.1 Planning the Review

Comparing this ontology to a real-life application of AVs such as the experiment Waymo is conducting in Phoenix, Arizona will show how the it 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 used the same data sources as in the first SLR, and used similar 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.

5.2 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 4 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.

We found 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.

We also found 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.

5.3 Reporting the Review

5.3.1 Waymo Experiment SLR. 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

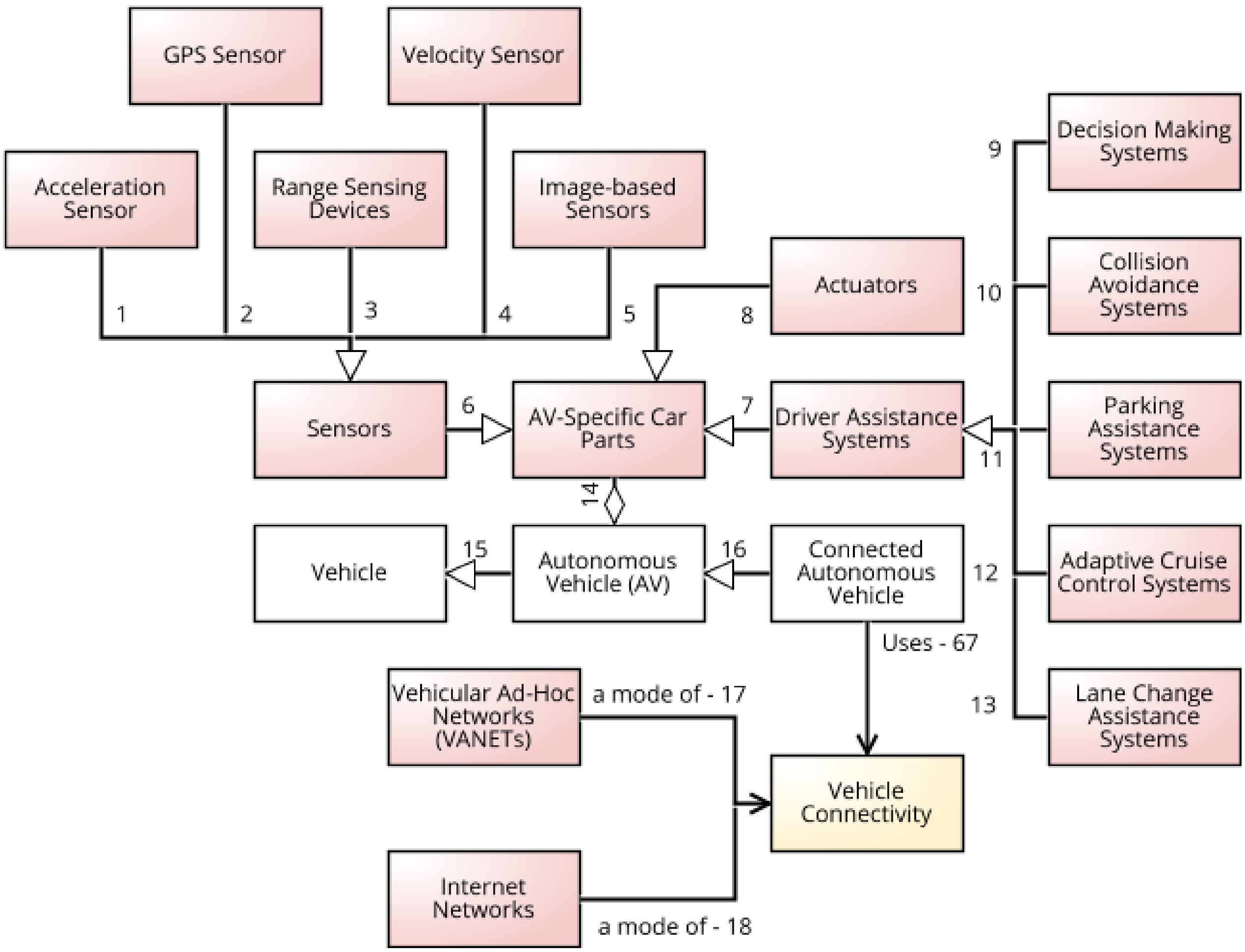

Fig. 1. Relationship between concepts of the Components module.

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 we have colored concepts where either 1)the concept was matched or 2) a child concept of the concept in question was matched. We can see virtually all the schema has been highlighted, showing all sections of the ontology have been validated.

5.3.2 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. In table 1 we were able to 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 in the answers originate in all three modules, substantiating the decision to segment the ontology into separate modules.

6 CONCLUSION

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

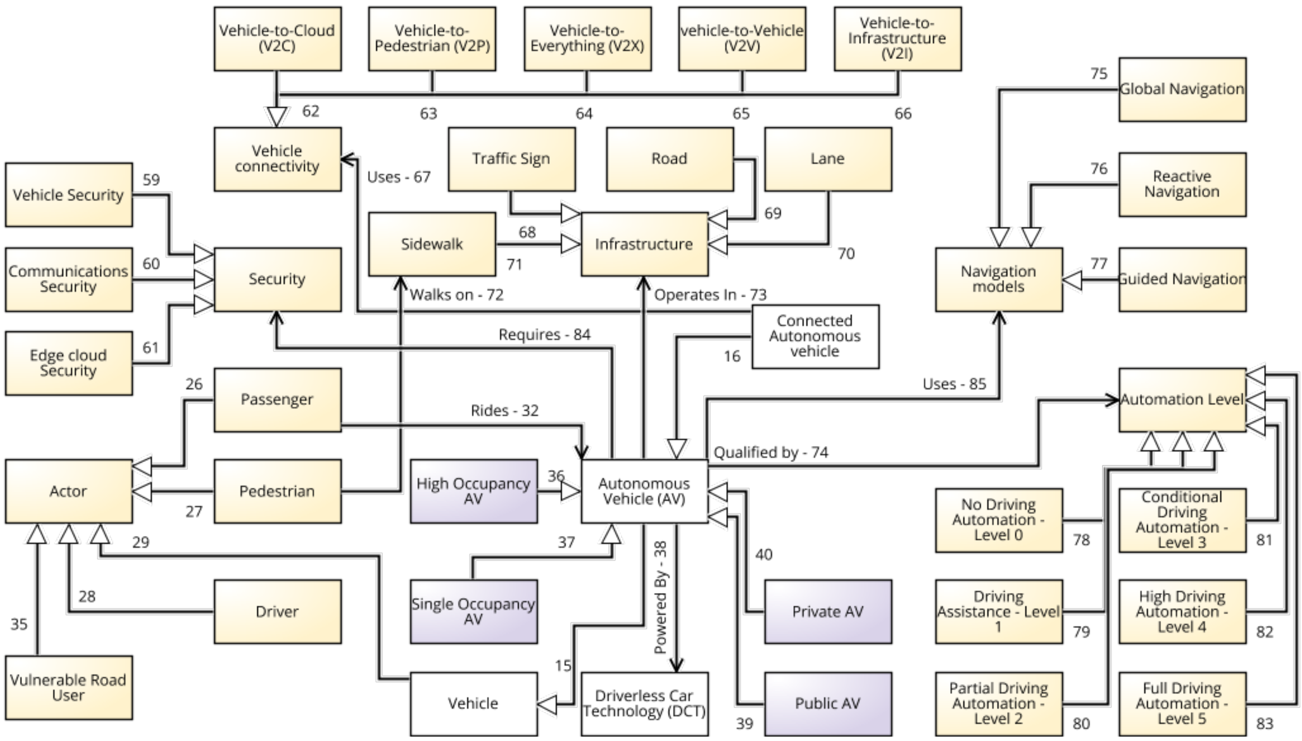

Fig. 2. Relationship between concepts of the Physical Environment module.

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.

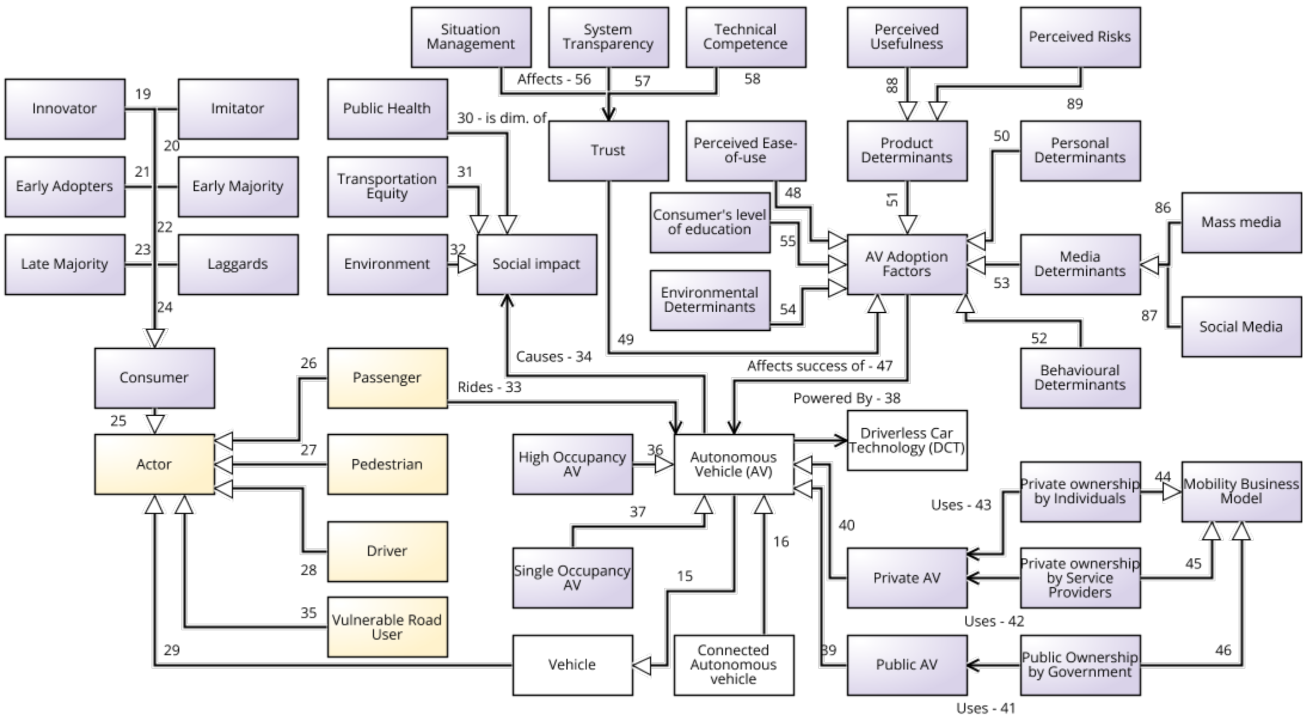

Fig. 3. Relationship between concepts of the social Environment module.

Table 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

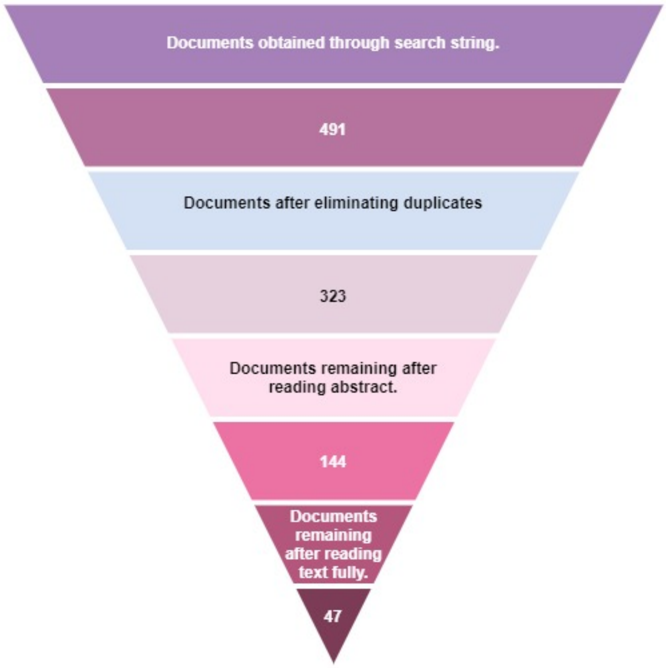

Fig. 4. Number of documents at each phase.

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. 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 [Kitchenham 2007].

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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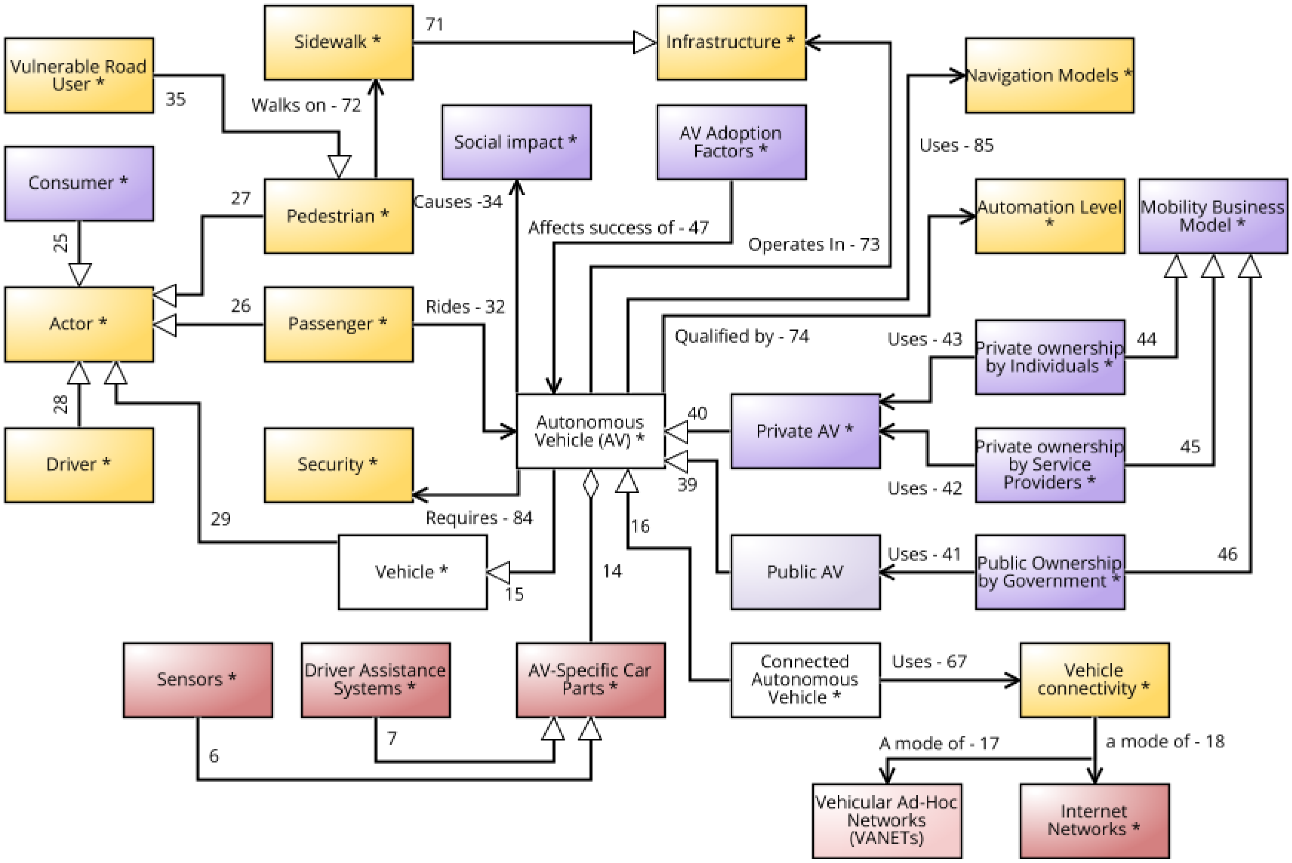

Fig. 5. Concepts matched in Waymo Experiment SLR.