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Autonomous Driving as System of Systems: current state and a future roadmap

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Abstract—Driving automation is probably the most trending research topic at the current time, with huge investments from governments, research centers, and private companies. The majority of the current research and development in this area is focused towards autonomous driving capabilities in a mixed environment. Having a reference model of what land transportation would look like once fully automated is challenging due to the complexity of such system, but important nonetheless for any planning activities in order to avoid wasting time and effort, and to accelerate the transition towards fully a fully autonomous transportation SoS. In this paper, we model land transportation SoS, propose an internet-inspired reference model for autonomous driving, and a roadmap for accelerating its development.

Index Terms—Autonomous Driving, System of Systems, Autonomous Vehicle Architecture, Intelligent Transportation Systems

I. INTRODUCTION

Driving automation is a very hot research topic at the moment, with huge investments from governments, research centers, and private companies, pushing the technology forward towards achieving a fully autonomous land transportation system. This new direction is motivated by the huge benefits expected from such evolution in transportation: driving automation is promised to increase safety by reducing fatal crashes, increasing road capacity by reducing congestions, leading to reduction in fuel consumption, etc. [1]. However, in the face of these benefits, there are challenges that will emerge as a result of this transition. Transitioning to autonomous driving will have social impacts on travelers behavior, how people perceive transportation, as well as economic impacts such as potential less manufactured vehicles, job losses in favor of automation, etc. Currently, driving automation is still in testing phase, with new technologies and strategies developed and tested by separated entities all around the globe. The most important challenge that faces driving automation however is not the technology, since currently there is a number of autonomous vehicles roaming the roads. Even though these are working almost all in controlled environments, however, the technology will become ready and available for use in the 2020s or 2030s [2]. The most important challenge is predicting the impact autonomous driving will have on its environment, and guiding the effort during the transitioning phase, in which human-driven vehicles and autonomous vehicles will share the roads. To accelerate this phase, and get the most out

of autonomous driving, it is important to plan this transition phase so that all major identified integration challenges are resolved beforehand, which prevent waisting time and effort. Planing these activities requires having a reference model, as to what autonomous driving would look like once deployed. This reference model, coupled with an assessment of land transportation as a System of Systems (SoS), allows us to study the effects of such SoS on other SoS that share its environment, and their effects on it. Using this analysis, in a series of iterations, our reference model may be refined to account for the results of these assessments, and plans for resolving potential challenges may be prepared beforehand.

This paper treats land transportation as a collaborative SoS, and driving automation as the next phase in its life cycle. Adopting this approach allows us to observe and understand land transportation's behavior by modeling each CS and understanding their interrelationships. However, land transportation exists within a larger SoS which consists also of water and air transportation, where each of the three transportation systems are related via physical and intangible relations, and therefore transitioning to autonomous driving also requires us understanding the relationships between land transportation and water and air transportation SoS. Moreover, the global transportation SoS exists also alongside other global SoS within Earth, the "super SoS". Economic SoS, energy SoS, and communication SoS are some of the global SoS that affect and gets affected by the global transportation SoS, which in turn, affect and get affected by land transportation, an instance within the global transportation SoS. This paper proposes a method for using such relations in order to identify key challenges that might slow down the transition towards autonomous driving, as well as refining our reference model for what would autonomous driving be like when fully deployed, both are important elements in planing transitioning activities from human-driven land to autonomous land transportation.

The rest of this paper is as follows: Section II introduces SoS, independent systems in the context of SoS, and provides a closer look on collaborative SoS. Section III provides a high level view on Earth as a super SoS, describes the different global SoS that exist within Earth super SoS, and focuses on ITS as a global transportation SoS. Autonomous driving is introduced as a SoS in Section IV, which contains a proposed model of that SoS, and a vision for its future. Section V presents this paper's contribution, a call for action , and finally,

Section VI concludes this paper.

II. SYSTEM OF SYSTEMS

System of Systems (SoS) are large-scale complex systems that consists of multiple independent systems, namely, constituent systems (CS) [3]. A SoS may be built by an authority to achieve a defined objective (or set of objectives), in this case, the SoS is said to be directed, where the authority defines the nature of relationships between CS, and how they should operate within the SoS. On the other hand, SoS may emerge because multiple independent systems are operating within the same environment. In this case, a system dynamics may be observed on a high level, and a virtual SoS emerges, which has unclear objectives, and an unknown structure. There exists 4 types of SoS : directed, acknowledged, collaborative, and virtual [4]. Figure 1 represents the different types of SoS separated based on 3 attributes: objectives, governance, and inter-relationship between CS.

SoS Objectives: Emergent					SoS Objectives: Recognized
SoS Governance: Community	Virtual	Collaborative	Acknowledged	Directed	SoS Governance: Centrally Managed
Inter-relationship: Independent					Inter-relationship: Subordinate

Fig. 1. Objectives, governance, and inter-relationship between CS are the 3 attributes that could be used to separate management taxonomies [5].

A. Independent Systems

The notion of independence in SoS is important and often used to describe CS that constitutes the SoS. Independence can be used to describe multiple aspects of a system: a system might be resource independent, human independent, etc. However, in the context of SoS, two specific aspects of independence are relevant: operational independence, and managerial independence. A system is operationally independent when it is capable of achieving its objectives by itself independently of any other system, whereas a system is managerially independent if all the decisions regarding mode of operation, resource management, etc. are made within the system itself. Figure 2 depicts an independent system scheme, in which operational and managerial parts are both within the system it self. For example, a human-driven vehicle, excluding the driver, is not operationally independent, however, if we consider the driver as well, the system (vehicle+driver) is operationally independent. Whereas an autonomous vehicle is operationally independent, but not managerially independent if we exclude the operator or owner who sets its objectives during operation. In the remainder of this paper, an independent system is a system that is at the same time operationally and managerially independent.

B. Collaborative SoS

Since the majority of SoS discussed in this paper are collaborative SoS, we will give in this section some aspects

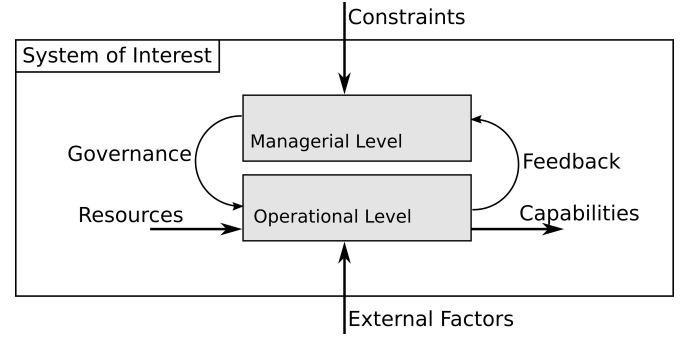


Fig. 2. An operational and managerial independent system scheme.

of such systems that are important to what we will be presenting. Collaborative SoS are any SoS which consists of a group of CS that work together voluntarily, because they share the same objectives. In this type of SoS, the rules that guide the evolution of the SoS, as well as the overall objectives are defined on the CS level collectively. Two best practices are relevant to the content of this paper and will be discussed in this section: interoperability between a vast number of heterogeneous systems, and SoS level coordination. To demonstrate these two aspects, we are going to use the internet as an example of collaborative SoS [3]. The internet emerged nearly 30 years ago as a directed SoS, and evolved to become a global network of networks which connects millions of computers, machines, and things all around the world, and became a transitioned to become a collaborative SoS from which we could extract lessons learned and best practices to adopt in our future collaborative SoS.

1) *Interoperability Between Heterogenous Systems*: This challenge is not exclusive to SoS, and is shared in all systems that consist of heterogeneous systems. In the context of SoS, the challenge is to find a way so that heterogeneous systems share information in a useful way that could be used across systems. In a traditional system, components are developed for a specific purpose, and interoperability is thought of during design phase. In contrast, CS in SoS are managerially independent, they have their own purposes, and use their own technologies and internal architectures, so the question becomes: how to design systems in a way that enable cooperation on system run-time? The solution to this challenge has two forms: technical standards and protocols. Technical standards are established norms or requirements in regard to a certain aspect of a system, such as architecture, methods, etc. Whereas protocols are a defined set of regulations and rules that determine how data is transmitted (communication protocols), and is used (service protocols) within a system.

2) *SoS Level Coordination*: SoS level coordination is essential in order to assure that SoS activities will lead to the desired outcome. At design time, SoS level coordination ensures that the global effort on CS level will achieve the desired SoS, which is done by identifying needs, providing guide lines and recommendations, and planing of the different activities. Whereas during run time, coordination effort is

focused towards monitoring the SoS, anticipating any potential failure, and making sure that the SoS is up to date with its CS, as well as its environment. Regardless of how coordination effort is performed, there exist a need for an entity that would take the responsibility of performing this SoS level coordination. In directed and acknowledged SoS, there is a SoS authority that is responsible for building that SoS, and coordination activities make an integral part of the activities of this authority. However, in collaborative SoS, this entity does not exist by nature, and it is up to CS to create this entity if needed. In the case of the internet, this entity is the Internet Engineering Task Force (IETF) ¹. From their page: “The mission of the IETF is to make the Internet work better by producing high quality, relevant technical documents that influence the way people design, use, and manage the Internet”. Even though the IETF does not have a coercive authority, the major actors in the internet adhere to its recommendations because it was created by them.

III. EARTH AS SoS

Autonomous driving as a SoS is part of a larger global SoS, namely intelligent transportation SoS. In order to understand autonomous driving, it is important to understand its place within this larger SoS, which in turn is also a part of a larger SoS, which is Earth. If we model Earth as a super SoS, we find that it consists of multiple global SoS, which are collaborative in nature. Figure 3 represents the major global SoS within Earth super SoS. Each SoS from Figure 3 is briefly explained

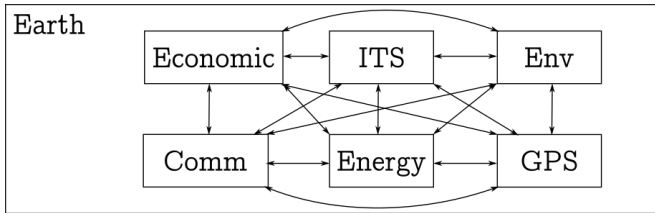


Fig. 3. Earth: a super SoS that consists of many SoS.

in the following:

- Economic SoS represents the global economic system, which consists of all stock markets, indexes, goods or services exchanges, etc.
- Env is the environment, which consists of climate, all natural phenomena (which may be destructive or not).
- Comm is the global communication SoS, which consists of the internet, mobile networks, communication satellites, etc.
- Energy as SoS is the group of all actors involved in the chain of transforming energy from its natural form to a usable energy source (electric, thermal, etc.).
- GPS is a global SoS that consists of satellites, their operators, maintainers, and service providers.
- ITS is the global SoS described in this section, which consists of land, air, and water transport in form of connected networks.

¹www.ietf.org

A. Inter-Relationships between global SoS

Each and every SoS shown in Figure 3 consists of multiple SoS, which might also exist within multiple SoS. The high level abstraction in Figure 3 shows relations between all global SoS. These relations consist of multiple types of relations, some are physical, such as data transferred by the global communication SoS, and others are moral, such as laws and regulations. On a lower level, a more detailed representation of these global SoS allows us to show these relations in further detail. For example, one of the many relations is the relation between environment SoS, communication SoS, and GPS SoS. Since satellites used in both communication and GPS SoS operate in the same environment (Earth orbit), they are both related to that environment, consequently, any human activity in that environment, or regulations concerning that environment, will affect both SoS.

B. Intelligent Transportation Systems

Intelligent transportation systems (ITS) (Figure 4) are any system, technology, service, or organization that has the objective of improving the state of any transportation system [6]. On a very high level, ITS is a global SoS which consists of governments, OEM, service providers, etc. Some of these CS work to improve the state of transportation in their local geographic region, such as governments that are interested only in their countries, while other contribute to ITS by providing global technologies that might be used within ITS (e.g. satellites that provide localization for vehicles). ITS is

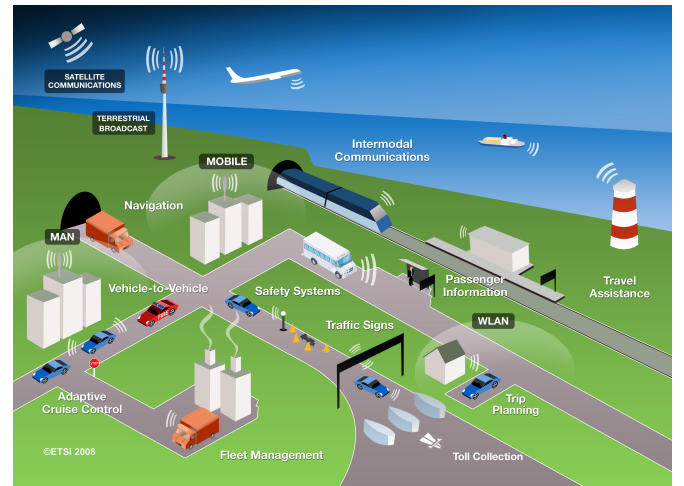


Fig. 4. Intelligent Transportation Systems: a global SoS [7].

a global SoS that exists alongside other global SoS, such as global economy, environment, global energy, etc. On a lower level, it consists of three global SoS, namely land transport, water transport, and air transport SoS (Figure 5). More specifically, within land transportation SoS, autonomous driving is the transition from human-driven vehicles to fully autonomous vehicles. This transition represents a big leap from the current transportation solution, to a fully autonomous solution, which promises huge economic benefits because

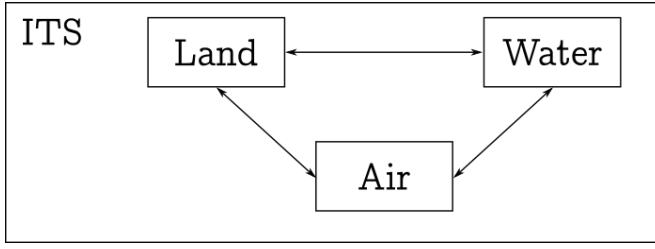


Fig. 5. Intelligent Transportation SoS: land, water, and air SoS.

of increasing road usage capacity for instance, and social benefits such as the reduction of the number of fatalities from car accidents. However, this transition is challenging because of the complexity of the SoS, and the nature of the technical challenge that we need to overcome by developing a fully autonomous vehicle. In the next section, we look at autonomous driving as a phase of land transportation SoS, in order to assess the current situation and to plan for the future.

IV. LAND TRANSPORTATION SoS

Autonomous driving could be thought of as the next step in transportation and mobility, it is not the end goal, but a mean to improve land mobility. In SoS engineering context, autonomous driving may be regarded as the next phase of the life cycle of land transportation SoS. Transitioning from the current phase to the autonomous driving phase is going to be done throughout multiple incremental phases of engineering activities. Planning these activities is very important in order to avoid wasting time and effort, and to accelerate the rate of development, and it requires us having some vision of what would the system look like when we reach that phase. Having this vision is challenging because land transportation is a complex SoS that consists of multiple complex SoS, and it operates in an environment shared between multiple SoS as well. This means that there are a lot of internal relationships that exist within the SoS itself, as well as external relationships between this SoS and other SoS, and consequently, it is hard to predict its future accurately. However, through some abstraction, and using high level representations, it is possible to plan for some aspects of the SoS, and provide recommendations and guide lines for any interested actor within this SoS.

A. Land Transportation SoS Model

According to the 2018 autonomous vehicles readiness index [8] by the KPMG company, autonomous driving consists of four pillars: policy and legislation, technology and innovation, infrastructure, and consumer acceptance. Each of these pillars has to be ready to accept and support autonomous driving in order to be ready for the transition to full autonomy. In a SoS context, each of these pillars is the requirements of a SoS within autonomous driving SoS. Figure 6 represents the model of land transportation SoS: legislation organizations, R&D organizations, infrastructure, and people.

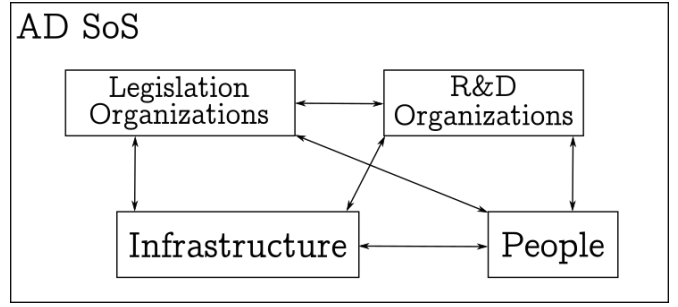


Fig. 6. Land transportation SoS: legislation organizations, R&D organizations, infrastructure, and people.

1) *Legislation Organizations*: Legislation organizations include governments, standardization organizations, and all organizations that are involved in setting laws, policies, and standards concerning any aspect of autonomous driving. Governments create laws and policies concerning autonomous vehicles, infrastructure, and fund research and development projects to accelerate the development of autonomous driving. They also provide incentives to people, manufacturers, and research teams for the same purpose. Governments may be working alone in an individual effort, or through collaboration with other governments. On the other hand, standardization organizations publish standards concerning different aspects of autonomous driving, such as communication, services, etc. By adhering to these standards, manufacturers and service providers save themselves from having to go through costly approval from governments. On the other hand, laws, regulations, and standards created by these organizations are being affected by technology and consumer requirements as well.

2) *Infrastructure*: Infrastructure in this context refers to the part of hard infrastructure used in autonomous driving SoS, such as road networks and telecommunication facilities. Hard infrastructure includes facilities for transportation, energy, water management, telecommunication, etc. Some of these facilities does not serve autonomous driving directly, e.g. water management infrastructure, whereas others do, e.g. transportation, telecommunication, and energy facilities. Infrastructure in autonomous driving SoS is the group of facilities that serve autonomous driving (Figure 7). While these facilities provide essential services for autonomous driving SoS, they are at the same time providing services to other SoS within their environment, for example energy facilities supply energy to buildings and establishments in addition to autonomous driving needs.

3) *R&D Organizations*: Research and development (R&D) organizations include private institutions, universities, manufacturers, and companies that develop technologies and solutions for autonomous driving needs. The spectrum of applications and subjects treated by these organizations range from technological solutions for technical challenges in autonomous driving, to customer related topics and ethical challenges. Organizations that publish technical reports regarding any aspect of autonomous driving are also included in this CS. legislation

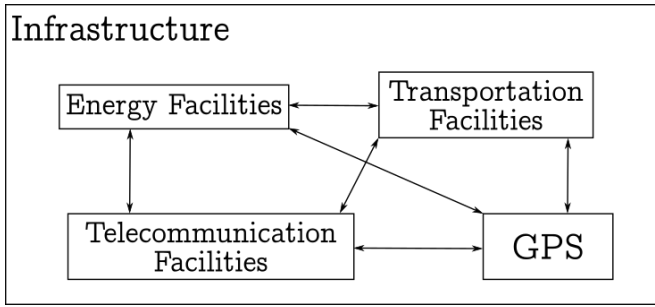


Fig. 7. Infrastructure SoS in Autonomous Driving SoS: telecommunication, energy, transportation, and GPS.

organizations may fund organizations from this CS to perform studies and provide recommendations concerning certain laws, whereas other organizations may provide solutions to technical challenges within infrastructure, while others contribute to consumer awareness and provide recommendations about ethical questions.

4) *People*: This CS consists of consumers of autonomous driving SoS services, workers and unions that are involved in this SoS at any level, as well as people that share its environment, or that are affected by it. For example, any technical solution for autonomous driving must take into account the presence of pedestrians, their detection and possibly avoidance. Another example is workers that might be replaced by autonomous driving once fully deployed. Every group of people is related differently to autonomous driving SoS, and they must be taken into account at all stages of development.

B. Land Transportation Reference Model

The exact future of autonomous driving is still unknown, and is very hard to predict. Several questions come to mind when we think about autonomous driving: would human still own cars or mobility as a service (MAAS) would become the adopted model? What will be the role of infrastructure? What will be impact on car manufacturers? It is hard to answer such questions at the moment because we are still at an early stage of development. However, land transportation is a SoS that has the objective of transporting people and goods from a source to a destination, which is almost the same objective as the internet, which is transporting data from a source to a destination. Each of these two systems is a collaborative SoS, and is composed from huge number of heterogeneous systems. Both SoS are governed by rules, laws, uses a physical infrastructure, and is in close contact with its consumers. A simple projection of land transportation on the internet model would provide us with the following reference model: streets are decomposed into sections characterized by their capacities. In each section, a backbone is responsible for monitoring traffic state, tracking vehicles within that section, providing various types of services to those vehicles. Vehicle route planing is done within the infrastructure using specific protocols that define time tables for vehicles in the form of spot reservation for a specific period of time. On vehicle level,

there will be a lot of applications that enable cooperation between vehicles, and this cooperation is incited by granting cooperation points to cooperating vehicles, which would be translated to priority of services from infrastructure, could be spent on services provided by another system within the SoS, etc. Obviously, the requirements on data transportation in the internet are different from the safety requirements on autonomous driving within transportation SoS, and this must be taken into account if such strategy is adopted. Of course this reference model may have multiple drawbacks when applied to transportation SoS, nonetheless, it might provide solutions to some of the challenges.

V. ROADMAP

So far we have seen that land transportation is a collaborative SoS which consists of multiple SoS, and is located in a larger SoS which in turn also consists of multiple SoS, and is located in a larger SoS. We have seen also a proposed reference model to autonomous driving that uses the example of the internet to extract lessons learned and best practices. But how this information could be used in a practical manner for the stated objectives? This section proposes a roadmap for activity planing, with the objective of accelerating the development and environment readiness for autonomous driving.

Step 1: Establishing a Collective Authority

As mentioned in Section II-B2, a very important aspect of collaborative SoS is the collaborative authority that performs SoS level coordination. The creation of such authority is essential in order to plan and guide the development of autonomous driving. Similar to the IETF, this authority will consist of representatives of major actors within land transportation SoS, as well as any concerned stakeholder. Some key activities this authority will perform are:

- Propose multiple reference models for autonomous driving
- Assess the current development effort in autonomous driving
- Create a detailed model of the current actors involved in the development of autonomous driving
- Propose architecture standards for autonomous vehicles and infrastructure facilities
- Propose protocols for service exchange between the different systems within land transportation SoS
- Assess the needs and challenges
- Propose solutions for the major challenges that will eventually face autonomous driving (for example a plan for the disposal of human-driven vehicles in the long term)
- Refine the models and documents regularly in order to ensure them being up-to-date with the SoS

Step 2: Propose multiple reference models

Having a reference model to what autonomous driving will look like is very important, as it gives a context to any entity that wishes to contribute to this domain, and it also

could be used with the other analysis results to predict and prepare for challenges. For example, all reference models of any automated transportation system involve only autonomous vehicles in the system. Using this information, we could infer that the current human-driven vehicles must be disposed of at a certain stage of deployment, which raises multiple questions: who will be responsible of disposing of these vehicles? what is the best way to do this task? will there be a need for new companies to do this job? and can these companies provide job for people whose job will be replaced by autonomous vehicles?

Step 3: Create a detailed model of the current land transportation SoS

As we discussed earlier, land transportation SoS consists of multiple SoS, and belongs to a larger SoS, which in turn consists of multiple SoS, and is part of a larger SoS. In order to fully understand the impact of autonomous driving on its environment, we have to take into account all of the relations that exist between land transportation SoS and all other SoS within its environment. This model consists of a introspective models that describe the internal architecture of this SoS, and retrospective models that describe the relations between land transportation SoS and other SoS. From introspective models we could acquire information such as the current needs, the maturity of the proposed solutions, etc. Whereas extrospective models could be used to predict the impact of a certain aspect of autonomous driving on other SoS in its environment, which in turn could be used to plan and prepare for any emergent behavior.

Step 4: Use the acquired information

After having a reference model (or group of reference models), and a map of relations between land transportation SoS and other SoS, we could simulate the different proposed solutions and strategies in the different reference models in order to study their feasibility, identify and prepare for emergent behaviors, anticipate challenges, propose guidelines and recommendations for the actors within the SoS. Examples include the preparation for human-driven vehicles disposal, studying the impact on power grids, can infrastructure be used to propose solutions for technological challenges in autonomous driving? etc.

Step 5: Update, refine, and repeat

These models and analysis must be revised regularly as appropriate in order to use any new information to refine models, predictions, proposed solutions or recommendations.

VI. CONCLUSION

Autonomous driving promises to change the way people perceive transportation, and is expected to improve the state of land transportation on social and economic levels. However, to accelerate the development and readiness for this solution, proper planning must be put in place whether to guide development activities, or to propose solutions for eventual challenges

that it will face. Land transportation is a SoS that exists alongside other SoS, and therefore any change within this SoS entails other changes in other SoS. Planning requires two main steps: having a reference model of what will autonomous driving will look like once fully deployed, and understanding the current state in details. Since land transportation is a collaborative SoS, establishing an authority in this SoS is essential to make sure that SoS level coordination exists and that the effort from the different actors within the SoS will lead to the desired SoS. This authority will have the job of proposing standards, protocols, and recommendations, as well as identifying needs and proposing solutions to anticipated challenges. Because the best way to predict the future is to plan for it.

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