Towards a Trust Management Approach Encompassing Stakeholders for the Automotive Ecosystem

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***Abstract*—The rise of connected services in modern vehicles, combined with the target of software-defined vehicles, makes new approaches to securing the automotive ecosystem necessary. One of these approaches is implementing computational trust models within vehicles to secure interactions in a way inspired by the intuitive concept of trust. Involved stakeholders and their relations are essential to creating a system representing trust. We identified relevant stakeholder groups involved in the communication of modern cars. We characterized them based on their lifecycle phase, the user agents and devices used to communicate, and their relations and roles. Furthermore, we describe the necessity for trust in the automotive ecosystem, the connection between trust and authorization, and the trust relations between the stakeholders. A formalization approach for the gathered knowledge about stakeholders and their characteristics is presented, utilizing a set-theory-based framework to review the definition of trust relations between stakeholders compared to proposed trust management systems. This approach shows that stakeholders in the automotive domain mainly gain their trust through their roles rather than their behavior. The difference between stakeholders and other entities is shown using the introduced framework. The provided stakeholder analysis, their roles in the automotive environment, and the formalization approach to linking stakeholders to trustworthy decisions are thus a basis for designing general trust management systems for the automotive ecosystem that cover multiple entity types.**

Keywords-automotive; ecosystem; trust; authorization; stakeholder; formalization.

I. Introduction

Modern vehicles offer various services to their passengers and the surrounding area. The interaction with devices and infrastructure outside of the vehicle is essential for these connected services that use different technologies like Vehicular Ad-Hoc Networks (VANETs) or mobile networks. With the integration of these technologies, the vehicle is no longer an isolated device. It becomes part of the Internet of Vehicles (IoV), a term inspired by the Internet of Things (IoT) to describe the ecosystem built by interconnected vehicles that makes use of an IoT-like architecture [2][3][4]. The functions aim to provide traffic functions or increase traffic safety by contributing to driver assistance or autonomous driving functions.

Different stakeholders interact with the ecosystem in this network to use functions or fulfill services. In this context, a stakeholder is defined as a person or organization that is in some way affected by decisions or actions, influences them, or even considers itself to be affected [5][6]. As multiple stakeholders are involved in the automotive ecosystem, it is a multi-stakeholder system.

In this multi-stakeholder system, trust is a relevant concept that is necessary for cooperation. Although trust originally is more a sociological and psychological concept that eases or enables decision-making between persons, it can be stretched to interactions with non-natural entities [7][8]. It describes the relation between two entities: a truster that places trust in services, data, or the general behavior of a trustee. Therefore, the stakeholders and their relations must be known in order to evaluate and define trust in a system. This also involves relations in automotive use cases, where misplaced trust can have severe consequences due to safety implications.

In computer science, computational trust is closely related to authorization systems. This is reasonable, as trust is a concept to decide about cooperation, and authorization is similar to such a decision. Especially use cases where a truster has to determine whether or not to use data provided by a trustee are comparable to a trustful decision process [9]. Use cases similar to this model are becoming more common with the rise of IoV.

For this purpose, this work aims to identify relevant stakeholders in the automotive ecosystem, assign appropriate characteristics, and describe their trust relationships. This builds a basis for trust models in automotive systems that secure communication between stakeholders and automotive systems. Therefore, the focus is on stakeholders that use electronic communication, excluding, e.g., contractual relations between stakeholders. Furthermore, only standard series vehicles are in scope, and no special vehicles, like emergency, driving school, or shared vehicles with specific adaptations, are included. A further restriction concerns the focus on vehicles in the scope of UN Regulation No. 155 that introduces mandatory measures to handle cyber security in the automotive domain [10]. This restriction is applied as we use the lifecycle introduced by this regulation. However, the results are not significantly affected by this limitation.

Based on this stakeholder analysis, we propose a formal framework describing the involved parties, their relations, and their trust in this context. This framework is built on set theory and function descriptions to allow more specific statements. Utilizing the proposed framework, we show how trust management systems work and why they only focus on interactions between artificial agents rather than including stakeholders. We propose a simple yet effective method to integrate personal or organizational entities into trust management systems by applying binary trust values according to the stakeholders' roles.

In summary, this paper contains the following contributions:

- Provide an analysis of stakeholders in the automotive ecosystem, their user agents, and the lifecycle phases they are active in
- Show how trust amongst the stakeholders is established
- Discuss the applicability of trust management systems on relations that include stakeholders
- Introduce a formal framework to describe trust-based decisions that contains stakeholders, and show how stakeholder relations can be included in trust management systems

This work is a follow-up to our paper [1]. We extended it with the formal framework and the approach to integrating stakeholders into trust management systems.

The rest of this paper is organized as follows. Related work is presented in Section II. This review shows that no comparable analysis exists. The necessary characteristics to describe the collected stakeholders are developed in the third section. Based on these parameters, the stakeholders are presented in Section IV. The results of the trust relation analysis are followed in the next section before these findings are further analyzed in the formal framework in Section VI. Finally, our findings are evaluated based on an exemplary case study. The last section summarizes the content of this work and gives an overview of its further use and limitations.

II. Related Work

Originating from project management, a stakeholder describes a person or organization that can affect or is affected by a decision or an activity [5][6]. This involves all entities that interact with the system in any way. Following Kosch [11], automotive stakeholders are connected to this specific environment in different steps, like the development, production, or usage phase. Furthermore, stakeholders can be categorized into different groups. Marner et al. [12] conducted a stakeholder analysis that mainly involves different stakeholders within an Original Equipment Manufacturer (OEM).

A comparable analysis was performed by Gomez et al. [13] with a focus on automotive digital forensics. The involved entities are necessary in this domain as their requirements are fundamental to answering forensic questions. This study presents two general stakeholder survey approaches: the brainstorming method based on Bryson [14] and snowball sampling as introduced by King et al. [15]. Only the first seems applicable, as the stakeholders in automotive digital forensics involve criminals, making a snowballing method including all stakeholders impossible. Using various brainstorming sessions with experts, a list of relevant stakeholders and a Venn diagram describing their main interests was created.

Mansor collected stakeholders regarding security in the automotive ecosystem [16]. This work also proposes a trust model for the automotive ecosystem, incorporating the three stakeholders OEM, service or application provider, and vehicle driver or owner. The trust relations between these entities are described. This model does not focus on trust relations on a technical level but instead on an interpersonal level.

Knauss et al. [17] collected a list of stakeholders and their relations in the automotive ecosystem. They gathered their information in interviews at an OEM and mainly focused on the interactions during vehicle development. As such, they did not focus on the electronic communication between stakeholders in the automotive ecosystem.

In various articles, trust relations are described using formal methods. Douceur [18] utilized a set-theory-based method to describe an attack threatening decentralized systems, including trust management systems. A formalized description of the trust concept by Marsh [19] has led to much attention and research in this field. This work uses set theory amongst function signatures with specific value ranges and the combination of the introduced variables using mathematical functions. Another approach using set theory by Habib [20] introduces propositional logic elements to specify the connection between elements and set memberships. Despite the various existing methods, the framework we introduce in this work focuses on a particular part of trust management systems in the automotive domain and provides new insights.

To our knowledge, a collection of stakeholders in the automotive domain and their trust relations and communication interactions does not yet exist. This gap also means that there is no formalized description. The present work will close this gap.

III. Automotive Stakeholder Characteristics

Appropriate characteristics are necessary to describe and characterize the collected stakeholders. For this work, three factors are considered necessary to describe stakeholders in the automotive domain. These consist of the lifecycle phase of vehicles the stakeholder is involved in, the user agents or devices used for communication, and the stakeholders' rights and responsibilities.

A. Automotive Lifecycle

Vehicle and vehicle projects are divided into several lifecycle phases. These phases are suitable to describe stakeholders, as several only appear in specific phases, and because they also take on different roles in different phases [11]. In this work, we combine two different methods to structure the automotive lifecycle. The first describes the *vehicle lifecycle*, whereas the latter focuses on the *vehicle project lifecycle*.

Hawkins et al. conducted a lifecycle analysis of battery-electric vehicles and used the three lifecycle phases *production, use,* and *end of life* [21]. Their approach is aimed at individual vehicles that are produced, used, and ultimately reused or disposed of, describing the *vehicle lifecycle*.

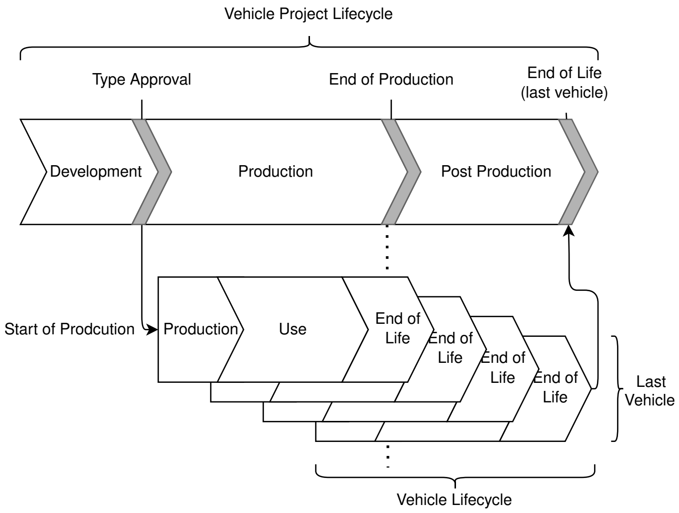

Figure 1. Vehicle Project and Vehicle Lifecycle in comparison.

The second approach targets vehicle projects, as the UN Regulation 155 does. In this regulation, the three phases *development, production,* and *post-production* are distinguished [10]. The phases seem similar to Hawkins' approach. Still, they cut the lifecycle of vehicle projects that are differentiated by the date of the type approval (between *development* and *production phase*) and the end of production date (between *production* and *post-production*). Individual end-user vehicles are only produced in the *production phase*. The last individual vehicle entering its *end of life phase* according to the *vehicle lifecycle* defines the end of the R155 *post-production phase*.

For this work, we assume stakeholders in both the vehicle individual and vehicle project-related lifecycle phases are relevant. Therefore, the generic lifecycle phases *development, production, use,* and *end-of-life* are utilized. We note that during the *development phase*, no publicly visible and customer-used vehicles are available. The *post-production phase* used in UN R155 is a phase to structure activities regarding the cyber security of cars after the *end-of-production* while vehicles are still in use. We argue that no additional stakeholders are involved in this phase compared to the *production phase*. Therefore, that phase is not considered explicitly in this work. Figure 1 overviews the lifecycle phases used.

B. User Agents used by Automotive Stakeholders

This work focuses on the security of the automotive ecosystem. As such, the electronic communication between the stakeholders and the communication within the automotive ecosystem is of central interest. As the presented stakeholders are natural, organizational, or legal entities, they use devices or interfaces for their electronic communication. As proposed by Kuschel in [22], we expand the vehicle to an interconnected automotive ecosystem that is used by various stakeholders to fulfill their workflows. This ecosystem consists of connected and communicating devices, which the stakeholders can use to interact with the ecosystem and other stakeholders. The ecosystem does not consist only of devices. Therefore, we use the term user agents for the relevant components of the automotive ecosystem, as stakeholders can utilize them for their communication.

TABLE I. USER AGENTS USED FOR COMMUNICATION IN THE AUTOMOTIVE ECOSYSTEM

User Agent	Description
Vehicle	Systems and ECUs contained inside the vehicle.
Backend	Applications on servers accessed online, often operated by the OEM or service providers. This user agent is distinct from frontends in the way that, in this case, the specific operator of the backend service accesses the service.
Diagnostic Devices	Devices used to interact with the vehicle's diagnostic system. Operations going beyond the legally prescribed actions like OBD [23] often require vehicle-specific information, which the OEM must also provide to non-affiliated workshops [24].
Frontends	Frontends for services accessed through the internet, including mobile apps.
RSUs	Devices located near street infrastructure that directly communicate with vehicles using VANETs.
Charging Station	Infrastructure to charge electric or hybrid vehicles.

These agents are listed in Table I and form a part of the automotive ecosystem. The list was created based on the stakeholder analysis and the evaluation of exemplary use cases originating in different lifecycle phases, like vehicle usage by end-users, online and workshop updates, the setup of new vehicles by customers, etc.

User agents must enable stakeholders to take on different roles based on their respective rights, which depend on the lifecycle phase.

C. Responsibilities and Rights in the Automotive Ecosystem

Interactions in the automotive ecosystem should only be possible if the acting stakeholder is allowed to make them. This authorization depends on the stakeholder, action, and context. One part of the context is the lifecycle phase the vehicle (project) is in. As such, the responsibilities and rights of automotive stakeholders are relevant characteristics and are, therefore, added to the stakeholders' description.

A simple but frequently discussed example of authorization is the application of software updates. While only the OEM can release and publish software for a vehicle, it is up to the owners of the cars to have it installed, as it entails a permanent change to the vehicle's condition. However, this division of tasks is only relevant in the use phase, as during development, the OEM itself has all rights to the pre-series vehicles and can, therefore, decide on changes to the condition itself. In the use phase, the authorizations to release and install software are divided among stakeholders, where the OEM maintains its products, but the owner decides on their property.

The vehicle ecosystem has to handle the relevant roles and responsibilities and consider changes within them if the lifecycle phase or, e.g., the ownership of the vehicle changes.

Otherwise, the ecosystem might not be able to correctly reflect contractual or business relations, leading to possible vulnerabilities. As this work provides an overview, such specific vulnerabilities are not in scope.

IV. Automotive Environment Stakeholders

The set of stakeholders, their relations, and interactions presented here was created using a comparable method as Gomez et al. [13] based on Bryson [14], as multiple brainstorming and discussion sessions, including various participants, were conducted. The stakeholders involved in the different lifecycle phases were collected within these sessions, and their roles were discussed. The participants included several employees of an automotive supplier, two employees of a start-up in the domain of decentralized identities with connections to OEMs and various suppliers, members of an automotive security research group partially with a background at different OEMs as well as a Professor researching in the automotive security domain.

Table II provides an overview of the stakeholders in the automotive ecosystem, the lifecycle phase they are active in, and the user agents they are using. The following section discusses the rights and responsibilities of each stakeholder.

a) OEM: During the development phase, the OEM is the driving force behind the development project, is responsible for its overall success, and bears the risk. This responsibility also means that the OEM has all the rights regarding communication and authorization in the ecosystem. These rights change when the vehicle is handed over to the customer. After that, the OEM no longer has direct physical access to the vehicle and can only communicate with connected vehicles via its backend. Indirect access is possible using the workshops, which receive instructions and tools for maintenance and repair from the OEM. The authorization to release changes to the vehicle, for example, through updates or modifications, can only lie with the OEM, as it must ensure compliance with regulations. The OEM remains involved after the utilization phase, as the reuse of components must be planned, for example, for second-life applications of batteries [25] or the use of spare parts from old vehicles, which may have to be approved for reuse in other vehicles [26].

For development, the OEM uses all clients that will be used in the later usage phase, even if only for testing purposes, as with RSUs. In later phases, direct communication between the OEM and the vehicle is only possible via the manufacturer-specific backend.

b) Supplier: OEMs develop new cars with the help of multiple suppliers. As supply chains get more complex, a distinction between different suppliers (Tier 1-3) is commonly used [17][27]. Suppliers get the task of developing, integrating, and supplying certain vehicle parts according to the requirements of the OEM. Their deliverable includes hardware (e.g., mechanical parts, ECUs) or software. With the shift from hard- to software-defined functions in vehicles [28] and the target of software-defined vehicles, together with the shift to more centralized E/E architectures [29], different suppliers need to work closely together to develop their functions.

How suppliers interact with the automotive ecosystem depends on the function they provide. There is no communication between the supplier and the ecosystem for mechanical parts, and there is no further interaction after the part's delivery during the production phase. For software functions, there are often additional activities for updates provided by the supplier or even direct interactions with the ecosystem in case of connected functions, such as if the supplier operates backend services or cooperates with service and content providers. The final diagnostic devices are utilized while developing the development interfaces of ECUs, especially in later development steps. This interface is provided by the OEM to enable suppliers to fulfill their tasks.

The limited communication between suppliers and the ecosystem reflects the supplier's rights in the use phase. As the vehicles' later users mainly interact with the OEM, and the OEM covers its suppliers, they do not have explicit, own rights or responsibilities in the ecosystem.

c) Development Service Provider: For certain activities during development, OEMs commission Development Service Providers to execute tasks, e.g., to test functions or devices regularly. For their activities during the development, the OEM grants them access to necessary parts of the ecosystem that can include all the systems an OEM also uses. They do not have explicit rights or responsibilities, especially not in later lifecycle phases.

d) Service and Content Provider or Operator: Modern, connected vehicles consume information from outside the vehicle and deliver their data to external services, forming the automotive ecosystem. To do so, data is provided by service providers, and infrastructure, such as mobile networks, RSUs or charging stations, are utilized that are operated by their operators. For the development of the connected services and the integration into vehicles, these stakeholders are involved in the development and production phase. During the use phase, they provide services, communicate with the vehicles, and are part of the vehicle ecosystem. Services are then mostly offered to the vehicle user, including specific rights and responsibilities according to their services.

e) Owner: Owners of vehicles are a heterogeneous group of stakeholders. Vehicles are owned either privately or for business. Business owners may again use cars for their business or provide them to others, e.g., car rental or sharing companies. Owners are distinct from the driver or user of the vehicle. Therefore, only fleet owners are considered in this study, as they can use special fleet services to manage their vehicles, although they do not directly use them. In this case, access to the vehicle ecosystem is possible through the frontends of fleet services. Furthermore, in the context of this work, the owner is regarded as the primary holder of the rights to his vehicle during the use phase, so the owner must authorize any changes. This assumption is subject to a restriction if the owner is the lessor of the vehicle and transfers it to the lessee

TABLE II. STAKEHOLDERS INVOLVED IN THE AUTOMOTIVE ECOSYSTEM. AN "X" MARKS THE LIFECYCLE PHASES THIS STAKEHOLDER IS INVOLVED IN AS WELL AS THE USER AGENTS THAT ARE UTILIZED.

Stakeholder	**Phases**				**User Agents**						**Description**
	Development	Production	Use	End of Life	Vehicle	Backend	Diagnostic Device	Frontends	RSUs	Charging Stations	
OEM	X	X	X	X	X	X	X	X		X	Develops, produces and sells the vehicle and is furthermore responsible for providing updates, service instructions, and service access
Supplier	X	X			X		X			X	Develops, manufactures, and delivers hard- or software for the product according to the OEM's requirements
Development Service Provider	X				X	X	X	X		X	Supports the OEM during the development by taking on specific tasks, especially testing
Service and Content Providers or Operators	X	X	X			X			X	X	Offer, adapt or develop services, that are integrated into the later product
Owner			X					X			Legally owner of the vehicle
Driver			X		X			X		X	Entity using the vehicle to drive
Workshops			X	X	X		X	X			Authorized and free workshops offering maintenance and repairs for vehicles
Authorized Test Organizations			X				X				Organizations authorized to verify the conformity of vehicles, e.g., in the PTI
Recycler				X	X		X				Manages recycling and disposing process

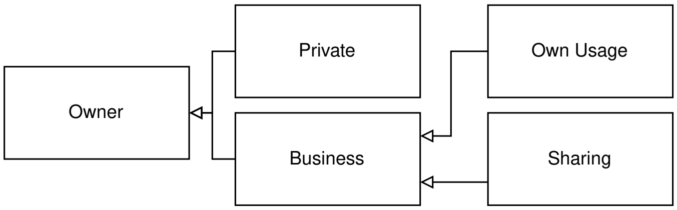

Figure 2. Different types of vehicle owners are divided into private and business owners. Business owners can use the vehicle for their own mobility or provide it as a rental or sharing company.

in its entirety. An overview of vehicle owner types is given in Figure 2.

f) Driver: Drivers are the actual users of the vehicle. They directly interact with the vehicle, its interfaces, and the frontends intended for end-users. Due to the distinction with owners, drivers have permission to use and drive the vehicle as intended, but they are, e.g., not allowed to manipulate or change the vehicle permanently.

g) Workshop: During the use phase, vehicles require workshops for maintenance and repairs. Electronic communication between the workshop and the vehicle becomes vital with more software functions. OEMs provide special equipment to access the necessary diagnostic interfaces. Due to legal reasons, access to these tools has to be given to independent workshops and must not be restricted to OEM partner workshops [24]. The owner authorizes the workshops to conduct repairs and maintenance, although this authorization is not currently represented in electronic communication.

h) Authorized Test Organization: To ensure the safety of vehicles on public roads, in various countries PTIs are legally required. Authorized Test Organizations carry these out. Communication with the vehicle is necessary during the test procedures, e.g., to access emission-related data via OBD [30].

i) Recycler: At the end of a vehicle's life, recyclers take care of its disposal and reuse. This also requires communication with the vehicle, for example, to trigger the end-of-life function of airbags, which releases the pyrotechnic elements and thus renders them harmless. This is done either via the vehicle's diagnostic system or by direct communication with the airbag control unit [31].

V. TRUST RELATIONS IN THE AUTOMOTIVE ECOSYSTEM

Trust is a characteristic of the relationship between two entities. In the computational trust domain, these entities are not restricted to be humans or organizations, they can also be devices equiped with algorithms that enable them to make decisions based on algorithms mimicking trust. In the automotive domain, three types of trust relations exist: trust between two stakeholders, natural or organizational entities as described in the introduction's description, one stakeholder and a device within the automotive ecosystem, and two devices of the automotive ecosystem.

The target of trust is to make decisions for or against cooperation, although one's own welfare depends on the decision and the behavior of another entity that can neither be controlled nor whose behavior can be predicted with certainty [7]. As such, it is closely related to authorization.

In the automotive ecosystem, such a mechanism can be embedded in an ECU that checks, e.g., the signature of a firmware update before installing it. In this case, the policy tests whether the firmware was signed with a specific key. For example, the OEM controls the necessary private key. This is reasonable, as the OEM is responsible for providing updates and keeping a vehicle safe and secure. The vehicle, therefore, trusts the OEM to provide firmware updates. In this simple use case with only one stakeholder, the OEM is also responsible for specifying and implementing the trust relation. The OEM must also include other relations, providing a particular gatekeeper position.

Trust always has to be considered in a specific context. As the vehicle trusts the OEM in the example above to provide valid software updates, the OEM is not authorized to open the vehicle in the use phase. The vehicle should not trust or follow a request by the OEM to open the car unless it was authorized to do so by the owner or driver of the vehicle. Such a use case becomes relevant if vehicles include functions to unlock them remotely.

Both examples describe an authorization scenario in which the vehicle, as part of the vehicle ecosystem, trusts a stakeholder in different contexts. The stakeholders' responsibilities and roles clearly define the trust relation.

For the sake of completeness, two examples of relations between stakeholders and between devices are given. The function "plug and charge" is considered for the first-mentioned. This function allows payment to be processed without the user's additional authentication. The user stores their data in the vehicle, which authorizes the charging station operator to process the payment. For the second category, direct communication between vehicles in VANETs can be considered, in which vehicles exchange information. No stakeholder is directly involved, and a trusting relationship arises between the two vehicles.

The following gives trust relations between the relevant stakeholders for each lifecycle phase.

a) Development Phase: The various stakeholders in the development phase are all authorized by the OEM responsible for the development process. Therefore, the OEM alone has the right to allow other stakeholders to communicate with the automotive ecosystem. The connections within the automotive ecosystem are also governed by the OEM that has complete control over the ecosystem in this phase. Trust relations between stakeholders and the ecosystem devices of all categories are managed by the OEM.

b) Production Phase: The structure of responsibilities in the production phase is similar to the development phase. The OEM is responsible for orchestrating the cooperation of involved suppliers, service, and content providers that might have to cooperate during production. For example, a Mobile Network Operator (MNO) might have to prepare the cellular network module during production. Again, the relations and the access are managed by the OEM.

c) Use Phase: When the vehicle is handed to the owner, there is a shift in the responsibilities and role structure. The OEM no longer has control over the entire ecosystem. Instead, the owner has extensive rights over its property and can, therefore, also determine which other stakeholders should interact with it. Beyond the scope of this work, it is necessary to discuss the extent to which vehicle ownership and physical control also justify exclusive rights concerning electronic interactions and to what extent a manufacturer may legitimately restrict these rights through End-User Licence Agreements (EULAs), particularly for services offered. Relations in the other direction are also possible, as service providers can authorize drivers to consume their services based on subscriptions.

More complex relations are possible as well. If we consider an OEM that releases maintenance instructions that have to be performed, the workshop usually receives them within their diagnostic systems. The owner can then authorize the workshop to execute these tasks.

As the rights in this phase are more distributed between stakeholders, this can lead to conflicts. An example of such a conflict led to the right-to-repair movement, where OEMs were forced to provide repair instructions and tools to free workshops alongside their partner workshops [24]. The regulation stated that the owner can decide which workshop should perform maintenance and repair tasks. In contrast, some OEMs wanted to restrict them to authorized workshops by withholding necessary tools. The access to the automotive ecosystem for third parties, as, for example, test organizations are, is often only possible by regulations that force OEMs to provide interfaces. As these interfaces are provided by regulation, there is no real trust or authorization connection between different stakeholders. From the automotive ecosystem perspective, all interactions compliant with the regulations are authorized.

d) End of Life: During the end-of-life phase, the disposal and reuse of the vehicle are the focus. OEMs have to enable the reuse of electronic vehicle parts that workshops can reinstall. Recyclers are responsible for safely disposing of parts that are not directly reusable and, therefore, need to communicate with the vehicle to disengage the airbags. The necessary interface for this interaction is based on regulation and, thus, does not have to be authorized by the OEM, and there is no real trust relation.

VI. Formal Framework

We create a formalized description of our findings to enable a more precise description of the entities and trust relations in the automotive domain. For this purpose, we utilize set theory to describe the different stakeholder groups, the user agents they use, and the lifecycle phases. These sets are then combined to explain the connection between these elements. A general approach to defining trust relations in the automotive domain is presented to show the integration of stakeholders in such a system. The difference between stakeholders and artificial agents implementing trust management algorithms is discussed, and a method to integrate both into a common system is presented.

A. Definition of Basic Sets

The formalization approach starts with the definition of various sets that describe the findings of the stakeholder analysis. The first set describes the stakeholders in the automotive domain. We define a set S that includes all stakeholders in the automotive domain. S has various subsets, one for each identified stakeholder group. Each of these groups is defined as a proper subset of S, as multiple of them exist, while most of the subsets (except for S_{Owner} and S_{Driver} that may include the same element) are disjoint.

- $S_{OEM} \subset S$ for OEMs
- $S_{Supplier} \subset S$ for the suppliers
- $S_{DSP} \subset S$ for Development Service Providers
- $S_{SCP} \subset S$ for Service and Content Providers or Operators
- $S_{Owner} \subset S$ for Owners, possible subsets for Private or Business Owners
- $S_{Driver} \subset S$ for Drivers
- $S_{Workshop} \subset S$ for Workshops, with possible subsections for free and authorized workshops
- $S_{ATO} \subset S$ for Authorized Test Organizations,
- $S_{Recycler} \subset S$ for Recyclers

As discussed in the stakeholders' description, the set S_{Owner} of owners can be divided into various subsets describing different, more specific vehicle owners. Following the structure in Figure 2, the set S_{Owner} includes the following subsets:

- $S_{PrivateOwner} \subset S_{Owner}$ for private vehicle owners
- $S_{BusinessOwner} \subset S_{Owner}$for business vehicle owners
  - $S_{DirectBusinessOwner} \subset S_{BusinessOwner}$ for business vehicle owners that directly use vehicles on their own
  - $S_{SharingBusinessOwner} \subset S_{BusinessOwner}$ for business vehicle owners that share their vehicles, e.g., to make money with them

Using this distinction, a more precise and detailed analysis of trust relations is possible.

Next, the utilized user agents are defined. For this, the subsets of A are defined as follows, representing a subset per identified user agent category:

- $A_{Vehicle} \subset A$ for vehicle client
- $A_{Backend} \subset A$ for backend systems
- $A_{DiagnosticDevice} \subset A$ for diagnostic devices
- $A_{Frontend} \subset A$ for frontend systems
- $A_{RSU} \subset A$ for RSUs
- $A_{ChargingStation} \subset A$ for charging stations

An equal definition is made for the lifecycle phases within the set $L = \{L_{Dev}, L_{Prod}, L_{Use}, L_{EOL}\}$:

- $L_{Dev} \in L$ for the development phase
- $L_{Prod} \in L$ for the production phase
- $L_{Use} \in L$ for the use phase
- $L_{Use} \in L$ for the end-of-life phase

In defining the basic sets, we distinguish between the stakeholder groups and the user agents as subsets and the lifecycle phases as members of their respective sets. For S and A, the defined groups or categories are subsets containing the specific elements, like a particular vehicle owner in S_{Owner} or a physical car in $A_{Vehicle}$. The set of lifecycle phases is a closed set with the four defined elements described in Section III-A.

B. Basic Mappings

The introduced set definitions allow us to formalize the basic connection between S, A, and L that have already been discussed.

Coming from the basic definitions in the previous section, we note that single elements out of sets or subsets are often used. The elements can be part of any subsets defined for the used sets if not specified further. For example, $s \in S$ means that s is any element in S, so it may be an element in S_{OEM}, $S_{Supplier}$, or any other subset.

One result of the stakeholder analysis is defined in Table II. It includes which stakeholder is active in which lifecycle state and which user agents are utilized by this stakeholder. A mapping describes the first outcome is

$$f_1 : S \to \mathcal{P}(L), \quad s \mapsto f_1(s) \subseteq L \tag{1}$$

where a stakeholder $s \in S$ is mapped on the power set of L, describing the lifecycle phases in which this specific stakeholder is active.

Next, the mapping

$$f_2 : S \to \mathcal{P}(A), \quad s \mapsto f_2(s) \subseteq A \tag{2}$$

describes which user agents a stakeholder utilizes.

These two mappings are also contained in Table II. New statements can be created if two parameters are combined.

$$\begin{aligned} g_1 : S \times A \to \mathcal{P}(L), \\ (s,a) \mapsto g_1(s,a) \subseteq L \quad \forall (s,a) \in S \times A \end{aligned} \tag{3}$$

$$\begin{aligned} g_2 : S \times L \to \mathcal{P}(A), \\ (s,l) \mapsto g_2(s,l) \subseteq A \quad \forall (s,l) \in S \times L \end{aligned} \tag{4}$$

The mapping 3 describes more precisely the lifecycle a stakeholder utilizes a specific user agent, 4 the user agents a client uses in a particular lifecycle phase. These mappings have been described in textual, the provided mappings can help to make more precise statements. An example is given for the stakeholder S_{OEM} that is active in the following phases and utilizes the following user agents:

$$1 : f_1(s) = \{Dev, Prod, Use, EOL\}, \quad s \in S_{OEM} \tag{5}$$

$$2 : f_2(s) = A \setminus A_{RSU}, \quad s \in S_{OEM} \tag{6}$$

A more specific statement can be created following the mapping 4.

$$\begin{aligned} 4 : f_2(s,l) = \{A_{Backend}, A_{Frontend}\}, \\ s \in S_{OEM}, l = \{L_{Use}\} \end{aligned} \tag{7}$$

The statement in (7) shows that an OEM has only a minimal possibility to access the vehicle ecosystem in L_{Use}.

C. Trust Relationships

This section discusses trust between entities in the automotive domain, especially the difference between the integration of stakeholders and other entities in these mappings.

Trust, as a characteristic of the relationship between two entities, is represented by the following term:

$$T_{x,y,z}, \quad x, y \in E, \quad z \in Z \tag{8}$$

Trust (T) is described as characteristic of the relation between a truster (x) and a trustee (y) out of a set of entities E in a situation or context (z), where $Z = \{z_1, z_2, ..., z_n\}$ describes the set of all possible contexts. As trust is a directed, not necessarily mutual relation between truster and trustee, $T_{x,y,z}$ is not necessarily $T_{y,x,z}$ [32]. If so, this results from the used model rather than being implied by the definition of trust.

An action can define a context, like opening a vehicle, retrieving information about a car, or changing its configuration through maintenance actions. Various other attributes can be considered in a context, like the time, location, or objects relevant to the action. As an example, a workshop (truster) might be authorized by the owner (trustee) to perform a specific software update (action) at its workshop (location) on the owner's car (object). For the simplicity of this work, we do not further distinguish the elements defining a context. As we focus on the role of stakeholders and their used agents, the three parameters of trustee, truster, and context are used here. However, other authors distinguish the various elements of the context and also see trustee and truster as part of it [33].

As stated earlier, truster and trustee do not necessarily have to be a natural or organizational entity. The stakeholder analysis was based on these two types of entities. Therefore, x, y are not necessarily contained in the set S, but in a more extensive set, described as the set of entities E, where $S \subseteq E$. $x, y \in S$ is valid for trust relations between two natural or organizational entities, as is the case for an owner authorizing a workshop to maintain a vehicle.

Electronic communication is especially interesting from a security point of view. In such situations, the communication between several entities has to be secured according to the trust relations of all involved entities. Next to the stakeholders S, other entities can be software functions in the user agents that provide functions to the stakeholders or for different user agents. In this case, the user agents do not act as simple clients to enable interaction with the automotive ecosystem for the stakeholders; they act as entities or agents themselves in a specific context.

The calculation of trust values in such systems can use various input parameters. Systems utilizing direct trust based on direct interactions between these entities can learn from the trustee's behavior and adapt the trust value according to past interactions, as the natural concept of trust does. Zhang et al. based their trust management system only on direct trust, as this does not require the definition of additional communication that might be hard to establish in the automotive domain [34]. Indirect measures can be used if other nodes share their experiences with an entity with others. The systems proposed in [35][36][37][38][39] are examples of the combination of direct and indirect trust paths. Although beneficial, especially in the VANET domain with highly dynamic network topology and high mobility [40][41][42][43], additional vulnerabilities can be introduced with wrong recommendations. Such attacks are often defined as good or bad-mouthing [44]. Subjective opinions are a core concept of trust, describing that every truster can trust a different trustee differently. Some proposed systems should be characterized more correctly as reputation systems, as reputation is a term for the public, cumulative knowledge about an entity's trustworthiness [45][46][47]. The possibility of forming a common opinion through consensus protocols without a central authority has led to a multitude of reputation systems in which the reputation values are formed using Distributed Ledger Technology (DLT) [48][49][50][51][52][53][54]. Apart from subjective, local values, the decisions in such systems are at least partially based on a globally synchronized value.

Apart from the behavior of nodes, other characteristics like their capabilities or competence can be integrated [46].

D. Trustful Decisions

Trust is a relationship characteristic used to decide if two entities cooperate. Restricted to electronic communication, binary decisions must usually be made. A trustful decision mechanism's binary output O is defined as follows.

$$O = \{allow, deny\} \tag{9}$$

We use the terms $allow$ and $deny$ here on purpose to illustrate the similarity to authorization mechanisms that use multiple input parameters to decide whether a service or resource (object) can be accessed by the subject in the requested way. Regarding trust management, the subject trying to access a service or resource is the trustee, the governing authority of the resource is the truster.

Following Jøsang in [9], the truster does not have to provide a service to the trustee. In some applications, like in VANET, the nodes share information with all their neighbors. Based on the application, the information source, and other attributes, each node decides whether the information is used or if the message is ignored. In this case, the node sharing the information is the trustee, and the consumer is the truster. The difference between traditional authorization systems and trust management and decision systems is that trust usually involves a subjective opinion of trustworthiness that might differ from entity to entity, and the truster's welfare somehow depends on the trustee. These characteristics are generally not given in authorization systems. These systems usually define a global policy utilizing objective attributes, as if someone holds an authorization token issued by a specific entity or provides valid credentials for which the necessary access rights are defined. In these systems, authorized entities can still be untrustworthy, for example, if inside attackers are considered [55].

An approach to defining a trust-based decision is given in the following function definition:

$$T_{x,y,z} \times \mathcal{P}(M) \to O, \tag{10}$$

In a trust-based decision process, the trust value between two specific entities x and y for this defined context z is used together with zero or multiple more attributes, where M establishes the set of all attributes.

The truster considers attributes when transferring a trust value into a trusting decision. Values considered here are usually not included in the trust value calculation. For example, Marsh [19] proposes quantifying competence, risk, and importance to decide how high the trust value has to be to enter cooperation. Mayer [56] regards risk as a central component in decision-making: a trust value reflects the risk that the trustee is willing to take, whereas the decision means that the trustee is taking the risk. This complies with the reliability and decision trust terms introduced by Jøsang [45].

One or more thresholds are a fundamental decision method based on trust value. As in many systems, a range is used as a metric for the trust, like $T_{x,y,z} = [0, 1]$ in [48][57][49][58][50], a threshold in this range can decide whether cooperation is entered or not. In some systems, multiple thresholds reflect decisions based on one trust value [38][53][52]. This can be reasonable if multiple alternative cooperation types or attributes are possible with more or less risk for the truster or if specific trust values trigger additional activities, like exclusion from the network [53]. Defining thresholds can be a complex task, so advanced methods like machine learning [59] or fuzzy set theory are applied by some authors [60]. The latter reflects uncertainty in categorizing trustees according to their trust values.

E. Binary Trust Values to Integrate Stakeholders

As defined above, a trust value describes a subjective opinion on the trustee's trustworthiness to behave as the truster expects. Various input parameters can be considered to determine these trust values.

This definition does not entirely comply with integrating stakeholders into trust management systems. In this case, the main reason for trust relations is the membership of a stakeholder group. For example, a workshop is authorized by the OEM to conduct maintenance measures according to the OEM's instructions because a workshop is defined as authorized to do so. A vehicle's owner can access the vehicle's data on the frontend because of its role. The trust relations involving a stakeholder are binary, as an entity either is in the necessary role for an action or is not. The trust value can only have two possible states in such a relation.

$$T_{x,y,z} = \begin{cases} 0, & \text{if } y \in S_a, S_a \text{ is authorized for } z \\ 1, & \text{if } y \notin S_a, S_a \text{ is authorized for } z \end{cases} \tag{11}$$

A ruleset based on contractual and legal requirements defines many trust relations in the automotive domain that include stakeholders. These requirements do not integrate a measure of the stakeholder's behavior or gain benefit from analyzing other attributes.

The integration of stakeholders into trust management systems can be achieved by applying the trust values given in Equation (11) to the stakeholders in specific contexts. These trust values, describing some blind trust and therefore not following the definition of trust relations [19][7] as the truster does not have a real choice, can reflect the permissions based on the stakeholder's role. As blind trust is used for a trust relations the truster is not questioning, in this case the term *given trust* suits better, as the trust relation is defined outside the context of truster and trustee by external, often contractual or legal conditions. The thresholds or other methods to make decisions on trust values must use this unconditional trust and always allow cooperation in necessary contexts, or deny it if the trustee does not have the required role. In these contexts, the system is comparable to a Public Key Infrastructure, which can be used to reflect unconditional attributes bound to an entity.

The proposed integration benefits from combining all types of trust relations in a common trust management system for the automotive domain. The trust value is used to decide whether or not to enter into cooperation. This trust value is calculated beforehand based on various input parameters, which may include the trustee's role. If such a role affiliation is relevant for a context, the binary determination of a trust value ensures the decision is made under this affiliation.

As part of the evaluation, we provide an example of how to implement the integration of a stakeholder into a trust management system.

VII. Evaluation and Exemplary Case Study

The results from this work are evaluated in various ways. First, stakeholders were discussed in different groups consisting of people working in the automotive domain and researchers in the automotive security domain. Secondly, exemplary scenarios were considered, and the stakeholders involved and their interactions were compared with the previous results. An excerpt of these scenarios is briefly presented below. The scenarios were selected to represent various trust relations, including different types of entities, as described in Section V.

The proposed formalization and integration of stakeholders into trust management systems in the automotive domain is described for each scenario.

a) Online Software Updates: In an online software update, the OEM provides new software for vehicle components that is usually downloaded over a backend connection and is installed without additional diagnostic equipment at the customer's location. In this case, the OEM is responsible for the overall process and approves the software before it is made available. Software may be supplied by suppliers but is tested and released by the OEM. Infrastructure operators are also included in the scenario to provide necessary services. Either the vehicle's owner or an authorized user usually approves the installation. Finally, workshops are involved in case the installation fails. Additionally, inspired by the terms of dis- and untrust introduced by Marsh et al. [61], a trust relation between the owner and the OEM might not even be necessary, as the owner may not have a choice other than installing mandatory updates, otherwise risking the shut down of the vehicle.

In a formal way, an entity $o \in S_{OEM}$ has the role of approving and releasing software installed on vehicles. Regardless of the developer of an update, the OEM is legally responsible for ensuring the safety of the software. The owner of a vehicle $e \in S_{Owner}$ has the right to decide what modifications are applied to his property. In a policy defining the decision, if an update is applied, the update client in the vehicle may refuse to install an update that is not signed by an entity $o \in S_{OEM}$ that has a specific role, e.g., *release-sw-update* or if the update is not wanted by the owner $einS_{Owner}$ of that precise vehicle, that has a role like *approve-sw-installation*.

b) Plug and Charge: The plug-and-charge scenario has already been briefly discussed in the trust section. In this case, the OEM has to provide necessary functions in the vehicle and the connected services (back- and front-end) to store the required information of a financial service provider that handled the payment. The driver then authorizes a charging station provider to request charging fees from the financial service provider.

To allow this use case, the vehicle owner or user has to enter into a contractual relationship with a financial service provider. The service provider then allows the owner's vehicle to charge while handling billing. In a document describing this relation, in a technical implementation, the financial service provider issues some kind of certificate, which the charging station then accepts to start charging. These relations are based on roles and contractual relations that can be implemented in a trust management system with the described approach.

c) VANETs: VANETs are a special network in which vehicles, RSUs, and other devices like mobile devices owned by Vulnerable Road Users (VRUs) communicate directly to exchange information about the current environment to enable cooperative driving functions or to increase road safety. In this scenario, devices within the automotive environment may communicate without the participation of a stakeholder. Involvement of service and infrastructure providers, operators, and drivers is possible, as advertised services are contained in the standardization of VANETs. Trust relations are interesting in this scenario, as no clear and pre-defined interactions exist in this ad-hoc network. Because of this, many automotive trust management systems concentrate on VANET applications [62].

Applying the proposed integration of stakeholders is unnecessary here, as no stakeholders are directly involved in the communication. This is one reason why trust in VANETs is so extensively analyzed, as there are no binary, pre-defined relations.

VIII. Conclusion and Future Work

Trust is an essential concept necessary for decision-making between people. The stakeholders involved and their relations must be known in order to evaluate trust and develop trust management systems in the automotive domain. As a comparable analysis did not yet exist, the relevant stakeholders have been collected in multiple sessions with different people working or researching in the automotive and automotive security domain. The interactions and trust relations between the collected stakeholders were determined by analyzing relevant use cases. To characterize the stakeholders, the lifecycle phase of vehicles in which they are involved, the user agents or devices they utilize to communicate in the automotive ecosystem, and their roles and responsibilities were used. The gained insights are used in a formalized framework to represent the findings more specifically. Based on the formal framework, the difference between trust relations between artificial agents, as studied in many trust management systems, and trust relations, including stakeholders, is discussed. An approach to integrate both types in a common system is presented by applying trust values to stakeholders at either end of the value range.

The stakeholders and their descriptions are general to provide an overview of the automotive domain. Although this was necessary for this work, it is a limitation, as in some scenarios, the same stakeholder groups are involved multiple times. A more in-depth analysis is required for specific scenarios. This also applies to the description of the automotive ecosystem, which can be considered in much more detail. Furthermore, the evaluation of the proposed stakeholder set can be extended to close possible gaps and ease the model's application in other studies. Moreover, the decision-making and enforcement of trust-based decisions, including the proposed approach to integrate stakeholders, will be discussed in future work. Despite the limitations, the insights gained can be used to define requirements for a trust management system that can map different use cases in the automotive ecosystem.

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