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How far can we go? Capturing Traffic Rules via Traffic Sequence Charts

Astrid Rakow, Jan Steffen Becker, Michael Wild, Eike Möhlmann
Institute of Systems Engineering for Future Mobility
German Aerospace Center (DLR)
Oldenburg, Germany
<firstname.lastname>@dlr.de

***Abstract*—The emergence of automated vehicles as active participants in traffic introduces new engineering challenges. Beyond traditional technical requirements, the engineers must now design systems that adhere to a complex set of regulations, ensuring compliance across a vast range of possible traffic scenarios. A formal specification of these scenarios is crucial–not only to facilitate communication between stakeholders during the development process but also to enable objective, tool-supported evaluation of behavioural requirements. Traffic Sequence Charts (TSCs) offer an intuitive, visual modelling language for the formal specification of traffic scenarios by representing them through sequences of images that are composed of symbols. Originally developed for the automotive domain, TSCs have been extended in recent years to cover also other transport sectors. In this paper, we demonstrate how traffic rules across the different domains–automotive, maritime, and railway–can be formally specified using TSCs as the same specification formalism. We highlight the advantages of using TSCs to capture complex regulatory requirements and discuss their strengths and limitations in general and specifically for the different domains. Finally, we outline a vision for integrating the TSC formalism into a holistic design framework for rule-compliant autonomous systems, identifying key challenges that need to be addressed and outline future work.**

***Index Terms*—traffic rule formalization, rule compliance, requirements engineering, runtime monitoring**

I. Introduction

Automated vehicles (AVs) are becoming integral actors across various transport domains, including rail, road, and maritime systems. As autonomy levels increase, these systems must not only navigate complex environments but also comply with domain-specific rules and regulations. Such compliance is essential for certification, safety, and public trust.

While traffic rules differ between domains—ranging from the highly deterministic rules of railway signaling to the context-dependent COLREGs in maritime navigation—all domains face the challenge of translating legal norms into system behavior. This challenge is amplified by ambiguities, exceptions, and the presence of human-centric conventions.

Traffic Sequence Charts (TSCs) [1] offer a visual and formal method for representing traffic rules through sequences of spatial scenes. Although first developed for automotive applications, TSCs are now being adapted across multiple transport domains.

This paper investigates the use of TSCs to formalize traffic rules in rail, road, and maritime domains. We highlight structural similarities and domain-specific challenges and outline how TSCs can support early-stage design, verification, and compliance monitoring in autonomous systems. This paper is structured as follows: Sect. II presents related works and introduces Traffic Sequence Charts (TSCs) as a modeling formalism. Sect. III discusses general challenges in the formalization of traffic rules. We present representative examples from the rail, road, and maritime domains and compare cross-domain characteristics in Sect. IV. Sect. V outlines our vision for embedding rule compliance in the development process. We conclude in Sect. VI.

II. Background and Related Work

Formal methods have long been used in safety-critical domains to specify and verify system behavior [2]. In the context of autonomous systems, the increasing complexity of operational design domains (ODDs) and the diversity of possible traffic situations demand tools that bridge high-level requirements and low-level behavior.

Scenario-based development has gained prominence as a central methodology for managing the increasing complexity of autonomous systems [3]–[5]. It supports structured system design, verification, and validation by decomposing real-world behavior into manageable abstractions [4]. A key refinement of this approach is the classification of scenarios into functional, abstract, logical, and concrete scenarios [6], [7]. Various tools and languages have been proposed for scenario modeling, including OpenSCENARIO [8] for simulation and traffic modeling. However, most scenario languages either sacrifice formal rigor (e.g. OpenSCENARIO) or readability (e.g. pure logic); TSCs provide both: a formal semantics as well as an intuitive visual representation. TSCs offer a diagrammatic notation for formally describing spatio-temporal traffic behavior. They decouple domain-agnostic semantics from domain-specific visualization primitives—as illustrated in the following. Each TSC consists of graphical scenes, called *spatial views (SVs)*, linked by composition operators (e.g., sequence, choice, concurrency) and optionally annotated with timing constraints. This enables precise, visual specification of behavioral requirements, which can be translated into linear-time metric logic formulas [1]. SVs are abstract: they visually define a traffic situation by its relevant aspects (e.g., spatial arrangement of vehicles on roads or trains on tracks). Thereby, they represent the set of all concrete traffic situations that match these aspects. For a full introduction to TSCs see [1]; here we only provide a brief overview due to space limitations.

Fig. 1 shows a TSC specifying that a white car overtakes a black car on the right. Initially, the white car is behind the black car[1]; then it is on its right and finally in front. The dashed boxes indicate that the white car can be located somewhere within that area. Each TSC begins with a declarative bulletin board that defines elements such as the ego vehicle. For simplicity this example omits the bulletin board. Further examples are given in Fig. 3, 5, and 6.

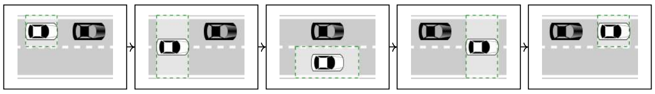

Figure 1: A sequence of five spatial views expressing that the white car overtakes the black car on the right.

TSCs are interpreted with respect to a formal world model developed for the system context. We assume the existence of an ontology that defines relevant concepts, artifacts, attributes, and relationships. This forms the semantic foundation for interpreting spatial and temporal constraints. Recent extensions and analyses have expanded TSCs' applicability in development workflows. For instance, SMT-based consistency checking by Becker [9] or monitoring approaches [10]. In this paper we will present the ongoing work of adapting TSCs to domain-specific needs.

Other approaches to formalizing traffic rules adopt complementary formalisms. For instance, Rizaldi and Althoff [11] use Higher Order Logic (HOL) to encode traffic rules and for checking compliance, while Sahin et al. [12] apply Signal Temporal Logic (STL) to express traffic constraints as optimization problems, enabling rule-aware planning. These logic-based methods focus on operational rule enforcement. In contrast, our TSC-based approach provides a visual scenario-specification formalism that aims to support early design phases, stakeholder communication, and formal verification, and may facilitate systematic test development across domains.

Bagschik et al. [13] propose an ontology-based framework for generating structured traffic scenes based on a layered model for scene representation. While their work supports scenario creation for simulation and coverage analysis, our focus is on formalizing traffic rules as behavioral constraints in dynamic settings. TSCs complement such modeling approaches by explicitly capturing rule compliance over time and space.

III. Challenges in Formalizing Traffic Rules

Before illustrating domain-specific applications of TSCs, we briefly sketch the general challenges involved in formalizing legal rules for automated systems by summarizing [14]. These

[1]The SV does not exclude other traffic participants or objects. Absence must be explicitly specified.

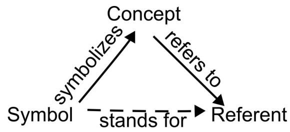

Figure 2: The semiotic triangle, relating symbols, concepts, and referents. [14]

challenges affect any translation of human-centric legal regulations into machine-interpretable specifications.

A central challenge in rule formalization is the so-called *congruence problem*—the difficulty of aligning a rule's legal interpretation with its technical implementation. This arises from the ambiguity of natural language and the differing conceptual models used by legal experts, engineers, and system designers. The semiotic triangle [15] models how humans express meaning: *symbols* represent linguistic identifiers, *concepts* denote their semantic interpretation, and *referents* are the real-world entities the concepts describe. Their relationship is illustrated in Fig. 2. A symbol (e.g., *"vehicle"*) represents an intended concept (e.g., *"a machine for transportation"*), which in turn refers to a set of real-world entities, or referents (e.g., the bicycle in front of your house). This mapping is often implicit and shaped by experience—people with different backgrounds may associate the same symbol with different concepts, or use different symbols for the same concept. Such misalignments, especially between legal experts, engineers, and autonomous systems, can result in errors during rule interpretation and also affects compliance monitoring.

As discussed in [14], several key challenges emerge from the congruence problem: 1) *Alignment*: Legal terms must be defined consistently by the involved stakeholders to prevent mismatches between interpretations when rules are formalized or monitored. 2) *Observability*: Abstract legal concepts must be mapped to perceivable observations. 3) *Vagueness*: Many legal terms like *"safe distance"* intentionally allow for interpretation. 4) *Uncertainty*: Sensor noise, environmental variability, and incomplete knowledge affect rule interpretation and compliance. 5) *Interrelations and Exceptions*: Rules often include dependencies, exceptions, or priorities that require careful modeling. 6) *Traceability and Justifiability*: Formalized rules must be traceable to their legal origins to ensure transparency and accountability. Legal rule interpretation is often shaped by implicit social norms and case law. This further complicates the direct encoding of rules into formal logic.

Facing these theoretical challenges of formalizing legal rules for automated systems, we like to note that they are of theoretical nature. Which means `(1)` that there are rules that are difficult to encode and some are even impossible to encode fully satisfactory. To our experience well suited approximations for many rules can already be formalized. For rules that need further concretisation or evidence, we envision feedback from monitoring rule compliance/violations to be used to improve the formalization. To this end, observers, derived from the formally specified rules, can be used. The rule can then be externally supervised by a comittee or the autonomous adaption adapts itself. (2) Legislation and regulatory frameworks for traffic have historically evolved with human participants in mind. Only recently have lawmakers begun to consider the implications of automated and autonomous systems as active traffic participants. As a result, the first legal adaptations are now emerging, and further, more comprehensive regulations are expected to evolve as the technology matures. For instance in Germany, the 2021 Act on Autonomous Driving established a legal framework for Level-4 vehicle operation within defined operational areas, with ongoing efforts at the national level to refine the technical details through accompanying regulations and at the international level to harmonize standards via UNECE and EU initiatives [16]. The European Union has updated its type-approval framework to accommodate fully automated vehicles [17]. In maritime transport, the International Maritime Organization (IMO) is working toward a goal-based MASS Code, expected in 2025, to provide a safety regime for Maritime Autonomous Surface Ships [18]. The current state of legal development varies significantly between domains, as we will discuss in the following section.

In all domains, a central challenge lies in translating legal regulations into technical specifications that autonomous systems can interpret and execute. Structured formalization methods, such as those based on Traffic Sequence Charts (TSCs), provide an intermediate layer between legal text and system behavior, supporting the development of rule-compliant systems. Despite theoretical limitations, we already successfully formalized a wide range of road traffic rules [14], and have also gained practical experience in formalizing maritime [19] and railway [20] traffic rules.

A. Formalization Approach

Fig. 4 describes our general approach for the formalization of traffic rules and the implementation of monitors. This figure was first presented in [14]. As an example, consider §4(1) of the German road traffic order (StVO) which states: *"In general, the distance to a vehicle in front must be large enough to stop behind it, even if it brakes suddenly. [. . .]"* As a first step, the terms and rules of the applicable regulatory text are assessed and clarified from a legal perspective, if possible. This provides the basis for the formalization. A description logic ontology is formed that contains the basic terms (concepts and roles) used in the regulatory text, like *"vehicle"* and *"in front of"* [21]. They are also called *"observable entities"*, as these are assumed to be entities recognized by a suitable perception chain. Building on this ontology, predicates and function terms are introduced that operate over the defined concepts. For the traffic rule above, the observable entities *"vehicle"*, and *"in front of"* can be identified, as well as a term *"enough distance"* which needs further clarification. Vehicles are *entities* in the ontology and therefore in a TSC represented by symbols (,). In contrast, *"in front of"* is formalized through the symbol placement in the spatial views (SVs). Fig. 3 shows the formalization of the traffic rule as a TSC. For a better understanding of the TSC, we rephrase the rule as *"If some vehicle B is in front of vehicle A, then A must keep enough distance to B."* The very first node in the TSC is the bulletin board introducing the two vehicles. Then there is a dashed frame, a so-called pre-chart, containing 2 nodes: The first is a grey hatched so-called true node, which expresses that initially anything may happen. Then, separated by a vertical dashed line, a node containing the spatial view for *"B is in front of A"* follows. The dashed frame constitutes the *"if"*-part of the rule. The last node, called the consequence of the TSC, expresses *"then A must keep a safe distance to B"*. Note, that *"safe distance"* is expressed with the help of a variable d_safe which needs further concretization. Scenario data can be collected by observing the real world (or a simulation). Rule observers that are derived from the formalized rule are used to judge whether the observed behaviour is rule compliant.[2]

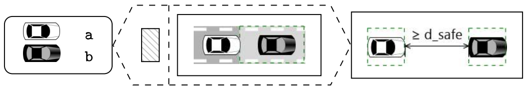

Figure 3: Keeping a safe distance to vehicles in front.

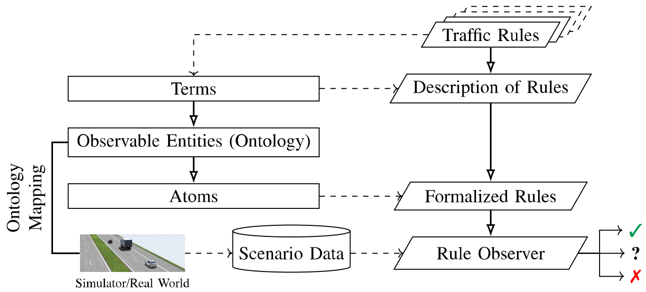

Figure 4: Approach for the formalization and observer implementation of traffic rules [14].

In the following we will give an overview of the domain specific challenges that arise.

IV. Domain-specific Applications of TSCs

A. Road Domain: Keeping a safe distance

Road traffic law is traditionally complex and layered, involving national road traffic regulations (e.g., StVO in Germany) and international agreements (e.g., Vienna Convention on Road Traffic [22]). Recently, countries like Germany have begun to explicitly regulate the deployment and behavior of autonomous vehicles, with legal frameworks such as the German Autonomous Driving Act [16]. However, many aspects—such as legal definitions of fallback responsibility, handling of ethical dilemmas, and liability—remain open or under debate.

In road traffic, ambiguity and high variability are major challenges. For instance, in §4(1) of the StVO used as an example in Sec. III, what constitutes *"enough distance"* de-

[2]The rule observer can not always decide whether the observed behaviour complies or not [14]

pends on speed, road conditions, and context, and is often left to interpretation.

Our approach [14] handles vagueness via dual interpretations for rule compliance and violation. They operate over the ontology of observable entities and allow partial reasoning in the presence of semantic uncertainty. The concept is grounded in the semiotic triangle, which highlights that vagueness arises when the conceptual meaning of a symbol fails to determine, even under perfect knowledge, whether a referent belongs to its intended interpretation class. This approach enables robust observer-based rule monitoring, even when the original legal language remains underspecified.

In joint work [14] with an Original Equipment Manufacturer, a law firm, and BTC Embedded Systems AG, we developed an approach to formalize traffic rules from the German Road Traffic Act (StVO) relevant to highway driving. This effort resulted in 111 formalized rules. Although TSCs were not used, we believe that all of the formalized rules can be expressed using TSCs with the benefit of better readability of spatial relations.

B. Rail Domain: Unprotected Level Crossing

Rail transport already operates within a highly regulated and deterministic framework, including detailed technical and operational rules (e.g., Germany's Ril 408). For the digital railway network a novel rulebook (upcoming Ril400) will move away from the existing functional structure to a process oriented one, featuring graphical process descriptions [23]. While existing laws do not yet explicitly target highly automated trains, the transition toward higher Grades of Automation (GoA3, GoA4) has triggered discussions about the sufficiency of current norms. Efforts are underway to integrate scenario-based approaches and to update regulations to account for reduced or eliminated human oversight. We present an exemplary rule formalization for scenario-based testing originally published in [20] and subsequently evaluated in [24]. In [20] we identified the need to extend TSCs for the railway domain in several ways: integration of railway symbols (from RiL 819), support for complex track schematics, communication events between trains and infrastructure, and criticality metrics tailored to rail safety. These adaptations enable TSCs to model railway-specific behavior and constraints at both the vehicle and operational levels. Most of these extensions are already supported except for communication events. Their full support has to be harmonized with other planned extensions.

Figure 5 shows a TSC that captures the formal rules for a train that approaches an unprotected level crossing, then has to stop and perform an acoustic signal, before it slowly crosses while no cars are approaching and no objects obstruct the track. The pre-chart capturing the *"if"*, defines the state before the crossing and the consequence ensures that the train only proceeds if no obstacle is detected.

C. Maritime Domain: COLREG Overtaking Rule

Maritime law is governed by international conventions, most notably the COLREGs. These were designed for human-

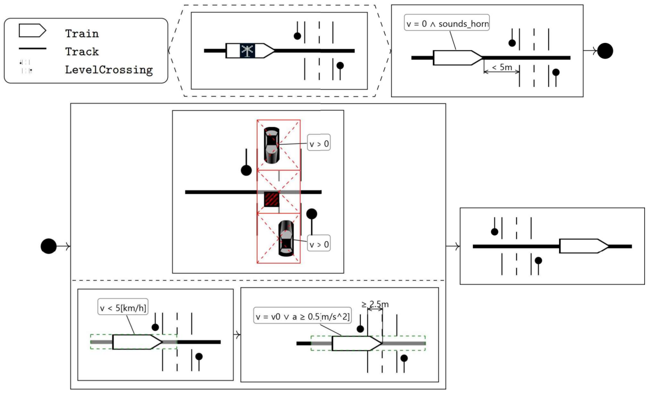

Figure 5: Intended behaviour at an unprotected level crossing [20]

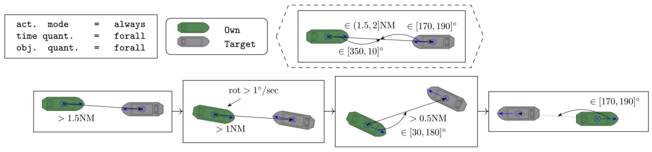

Figure 6: Formalization of the head-on rule [25]

operated vessels and include rules that rely on subjective judgment (e.g., *"safe speed"* or *"early and substantial action"*). The rise of Maritime Autonomous Surface Ships (MASS) has prompted organizations like the IMO to launch regulatory scoping exercises. Progress is ongoing, but no binding legal framework specifically for fully autonomous vessels has yet been established.

Fig. 6 shows how the COLREG head-on rule is formalized using TSCs. The two vessels are denoted as *Own* and *Target*. When *Own* detects *Target* within 1.5–2 nautical miles and at a heading angle within $\pm 10°$, it must, before the distance drops below 1.5 nautical miles, alter course to starboard at a rate exceeding 1°/s. This maneuver must maintain a separation over 1 nautical mile until *Target* appears at a relative bearing of 30°–180°. From that point, *Own* must continue on *Target*'s starboard side, keeping at least 0.5 nautical miles distance, until *Target* passes behind at a bearing of 170°–190°.

To adapt TSCs to maritime navigation, several extensions were introduced [19]. In the above figure, dedicated directional attributes such as heading and course over ground (COG) are visualized via direction anchors. Enhanced relative spatial relationships express bearings between vessels, which are crucial for collision avoidance. These extensions enable precise specification of COLREG-compliant behavior, where geometry, visibility, and dynamic context are essential to rule interpretation.

D. Cross-domain Comparison and Discussion

Despite differing modalities, traffic rules in rail, road, and maritime domains share a common goal: ensuring safe and orderly coordination among multiple agents in shared operational spaces. TSCs support this goal by providing a structured means to express *temporal order*, specifying that actions such as yielding, slowing, or signaling must occur in a defined sequence, and to capture *conditional behavior*, where decisions like *"proceeding at a level crossing"* or *"entering a highway"* depend on specific environmental or system states. Because every TSC can be automatically translated into temporal logic, such safety-relevant patterns become formally analyzable—enabling consistency checks, rule monitoring, and traceable links between requirements, system behavior, and test specifications with the TSC framework.

The three domains differ significantly in how traffic rules are formulated and enforced. In *road traffic*, rules are numerous, context-sensitive, and often under-specified. Their encoding must therefore account for ambiguity, variability, and legal interpretation—often tied to perception states. In the *rail domain*, rules are deterministic, infrastructure-bound, and centrally enforced. While formal verification (e.g., model checking) is well-established for components like interlockings and ETCS subsystems (e.g., subset-076), TSCs offer value for modeling operational processes that involve the open world, including perception tasks currently performed by the train driver. In the *maritime domain*, COLREGs depend heavily on mutual interpretation, environmental conditions, and negotiated interactions. Here, TSCs must capture spatio-temporal geometry and context-dependent rule compliance.

E. Implications for Certification and Tool Support

Across domains, TSCs support scenario-based development. They offer a formal *specification*, facilitating communication among experts, engineers, regulators, and test designers. As a formal language, TSCs support both rigorous SMT-based consistency checks [9] and structured validation via maintainable scenario catalogues. Because every scenario and rule is encoded in the same formalism, the specification provides a foundation for tool-supported querying, reuse, and analysis—e.g., for consistency, containment, or completeness. While exhaustive analysis may be constrained by decidability and performance limits, the unified formalism enables explorative reasoning and structured verification workflows across domains. Our in-house experience shows that this domain-independent analysis—from specification to run-time monitoring (cf. [26])—helps align legal intent with rule formalization. Ongoing work explores extensions to broaden TSC tooling for complex autonomous systems.

V. Towards Designing Rule Compliant AVs

To illustrate the potential of TSCs to support the development of rule compliant systems, we outline an envisioned tool chain with the well-established V-model (cf. Fig. 7) used in the automotive domain and similarly applied in the rail domain. This model describes a structured development process that incrementally refines the system under development (SUD) until all components are realized. These are then integrated and tested stepwise, until system-level and acceptance testing

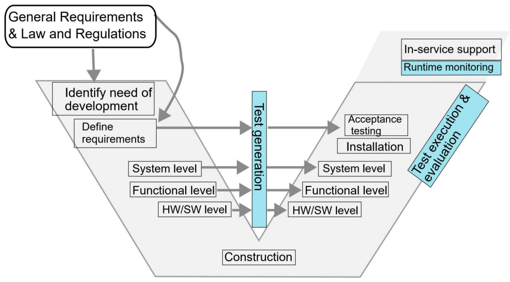

Figure 7: The V-model

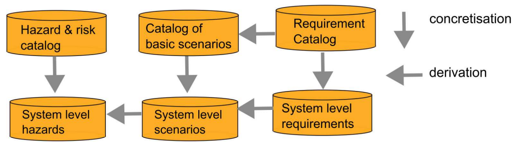

Figure 8: TSC for requirement definition and system level analysis

before deployment. While the V-model illustrates a classical sequential approach, modern adaptations emphasize front-loading of verification and validation into earlier development phases—often before all components are fully realized or physically integrated.

Fig. 8 illustrates key artifacts in the design of a safety-critical automated system, where TSCs are envisioned as core modeling tools. In the early phase of the V-model, legal regulations and domain-specific traffic rules already shape system requirements. Changes in legislation may trigger new functionality or adaptations. TSCs can formalize and visualize rule-based requirements from the outset, and support the collaborative development of *"basic scenarios"* that capture essential system use cases. These basic scenarios serve as a key input for the subsequent hazard and risk analysis. Once an abstract system architecture is available, engineers identify potential hazards using existing hazard databases and structured brainstorming. The approach in [27] systematically derives hazardous scenarios to explore possible failure modes of the SUD. By applying keyword-driven brainstorming, basic scenarios are concretized into hazard scenarios that reflect both the operational context and the initial system architecture. The resulting scenarios, formalized as TSCs, support traceability, link requirements to safety concepts, and guide later test development. Formal monitors can be synthesized to observe runtime behavior and detect rule violations, enhancing both early validation and test coverage.

Embedding TSCs throughout the V-model lifecycle—from requirements to test interpretation—enhances transparency, stakeholder alignment, and safety assurance. Their visual form helps diverse stakeholders collaboratively refine vague regulatory requirements into concrete scenarios. These scenarios then support test case generation and outcome interpretation; for instance, a failed TSC monitor can directly indicate a deviation from expected rule-based behavior.

Formal monitors are a key component in developing rule-compliant autonomous systems, as they assess whether system behavior adheres to specified rules. Initial approaches for synthesis of TSC monitors have been proposed, with ongoing research extending their capabilities [10]. These monitors can be deployed in simulated, hybrid, or real-world environments to monitor rule compliance during development as well as after deployment. Beyond validation, they also enable the generation of compliance-relevant logs from black-box system runs. When systems support feedback propagation, monitoring results may further inform self-adaptive learning or external refinement of the rule base.

Moreover, TSCs can serve as a structured catalogue of the knowledge required to fulfill system requirements—of which legislative rules are a special case. The formalized requirements provide a foundation for testing whether the system possesses the relevant knowledge to act in compliance.

VI. Conclusion

Through representative examples, we demonstrate how Traffic Sequence Charts (TSCs) capture spatio-temporal traffic rules across rail, road, and maritime domains both visually and formally. As a formal specification language with customizable visualization—for e.g. track schematics, road layouts, nautical bearings—TSCs aim to enhance comprehensibility for diverse stakeholders. They support early-phase requirements engineering and later enable automated consistency checks, runtime monitoring, and scenario-based testing, all without changing the underlying semantics or verification toolchain.

Future work will integrate our TSC-based approach into certification workflows, linking formal rule specifications with evidence generation and regulatory scenarios. We anticipate this will yield improved traceability, earlier detection of rule conflicts, and streamlined cross-domain reuse of verification techniques.

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References

[1] W. Damm, E. Möhlmann, T. Peikenkamp, and A. Rakow, *A Formal Semantics for Traffic Sequence Charts: Essays Dedicated to Edward A. Lee on the Occasion of His 60th Birthday*, 07 2018, pp. 182–205.

[2] J. Rushby, "Formal methods and their role in the certification of critical systems," in *Safety and Reliability of Software Based Systems*. Springer, 1997, pp. 1–42.

[3] G. Bagschik, T. Menzel, and M. Maurer, "Ontology based scene creation for the development of automated vehicles," in *2018 IEEE Intelligent Vehicles Symposium (IV)*, 2018, pp. 1813–1820.

[4] A. Sutcliffe, "Scenario-based requirements engineering," *IEEE Transactions on Software Engineering*, vol. 24, pp. 320– 329, 10 2003.

[5] S. Riedmaier, T. Ponn, D. Ludwig, B. Schick, and F. Diermeyer, "Survey on scenario-based safety assessment of automated vehicles," *IEEE Access*, vol. PP, pp. 1–1, 05 2020.

[6] C. Neurohr, L. Westhofen, M. Butz, M. H. Bollmann, U. Eberle, and R. Galbas, "Criticality analysis for the verification and validation of automated vehicles," *IEEE Access*, vol. 9, pp. 18 016–18 041, 2021.

[7] T. Menzel, G. Bagschik, and M. Maurer, "Scenarios for development, test and validation of automated vehicles," in *2018 IEEE Intelligent Vehicles Symposium (IV)*, 2018, pp. 1821–1827.

[8] Association for Standardization of Automation and Measuring Systems, "Asam open scenario," https://www.asam.net/standards/detail/openscenario/, 2021, accessed: 2025-04-09.

[9] J. S. Becker, "A consistency analysis method for traffic sequence charts," in *VEHITS24 Doctoral Consortium*, Mai 2024. [Online]. Available: https://elib.dlr.de/204347/

[10] D. Grundt, A. Köhne, I. Saxena, R. Stemmer, B. Westphal, and E. Möhlmann, "Towards runtime monitoring of complex system requirements for autonomous driving functions," *Electronic Proc. in Theoretical Computer Science*, vol. 371, p. 53–61, Sep. 2022.

[11] A. Rizaldi and M. Althoff, "Formalising traffic rules for accountability of autonomous vehicles," in *2015 IEEE 18th Int. Conf. on Intelligent Transportation Systems*, 2015, pp. 1658–1665.

[12] Y. E. Sahin, R. Quirynen, and S. D. Cairano, "Autonomous vehicle decision-making and monitoring based on signal temporal logic and mixed-integer programming," in *2020 American Control Conference (ACC)*, 2020, pp. 454–459.

[13] G. Bagschik, T. Menzel, and M. Maurer, "Ontology based scene creation for the development of automated vehicles," in *2018 IEEE Intelligent Vehicles Symposium (IV)*, 2018, pp. 1813–1820.

[14] L. Westhofen, I. Stierand, J. S. Becker, E. Möhlmann, and W. Hagemann, "Towards a congruent interpretation of traffic rules for automated driving - experiences and challenges," in *Proc. of the Intern. Workshop on Methodologies for Translating Legal Norms into Formal Representations (LN2FR 2022) in association with JURIX 2022*, G. Borges, K. Satoh, and E. Schweighofer, Eds., Dezember 2022, pp. 8–21. [Online]. Available: https://elib.dlr.de/193009/

[15] C. Ogden and I. Richards, *The meaning of meaning: A study of the influence of thought and of the science of symbolism*. Harcourt, Brace & World, 1923.

[16] Bundesministerium für Digitales und Verkehr, "Gesetz zum autonomen Fahren," https://bmdv.bund.de/DE/Themen/Digitales/Digitalisierung-der-Mobilitaet/Autonomes-Fahren/autonomes-fahren.html, 2021, accessed: 2025-04-08.

[17] T. Group, "Fahrerlos durch Europa: Neue Regelungen für autonomes Fahren," https://traton.com/de/newsroom/stories/regelungen-fuer-autonomes-fahren-fahrerlos-durch-europa.html, 2022, accessed: 2025-04-08.

[18] International Maritime Organization, "Symposium on "Making Headway on the IMO MASS Code"," https://www.imo.org/en/MediaCentre/MeetingSummaries/Pages/Symposium-on-%CA%BAMaking-headway-on-the-IMO-MASS-Code%E2%80%9D-.aspx, 2023, accessed: 2025-04-08.

[19] A. Austel, M. Steidel, and B. Westphal, "Formal specification of traffic scenarios in scenario-based testing of maritime assistance systems," in *MARESEC*, 2024. [Online]. Available: https://doi.org/10.5281/zenodo.14214762

[20] M. Wild, J. S. Becker, G. Ehmen, and E. Möhlmann, "Towards scenario-based certification of highly automated railway systems," in *Reliability, Safety, and Security of Railway Systems. Modelling, Analysis, Verification, and Certification*. Springer, 2023, pp. 78–97.

[21] F. Baader, D. Calvanese, D. L. McGuinness, D. Nardi, and P. F. Patel-Schneider, Eds., *The Description Logic Handbook: Theory, Implementation, and Applications*. Cambridge University Press, 2003.

[22] United Nations Conference on Road and Motor Transport, "Convention on road traffic geneva, chapter XI," https://treaties.un.org/doc/Treaties/1952/03/19520326%2003-36%20PM/Ch_XI_B_1_2_3.pdf, 2021, accessed: 2025-04-08.

[23] J. Pachl, "Operational Rules for the Digital Railway," *ZEVrail*, vol. 146, Feb. 2022.

[24] M. Wild, J. S. Becker, C. Schneiders, and E. Mohlmann, "A Scenario-Based Simulation Framework for Testing of Highly Automated Railway Systems," in *Proc. of the 11th Int. Conf. on Vehicle Technology and Intelligent Transport Systems*. SCITEPRESS, 2025.

[25] A. Austel and G. Hake, "TSC monitoring in FuturePorts," German Aerospace Center, project report, Mar. 2024, unpublished.

[26] A. Rakow, G. G. Gasiola, D. Grundt, J. Collenette, E. Möhlmann, and M. Schwammberger, "From data-compliance to model-introspection: Challenges in AV rule compliance monitoring," 2025, Proc. of the Intern. Workshop on Lawing4AV in association with IAVVC 2025; accepted.

[27] B. Kramer, C. Neurohr, M. Büker, E. Böde, M. Fränzle, and W. Damm, "Identification and quantification of hazardous scenarios for automated driving," in *Model-Based Safety and Assessment*. Springer, 2020, pp. 163–178.