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MUSICC: An open catalogue for CAV certification scenarios[†]

Zeyn Saigol[1*], Robert Myers[1], Alan Peters[1], Tim Edwards[2]

1. Connected Places Catapult, UK

* zeyn.saigol@cp.catapult.org.uk

2. HORIBA MIRA, UK

Abstract

The MUSICC (Multi User Scenario Catalogue for CAVs) project has produced an open source scenario database, intended to prove the concept of using scenario-based tests as part of a CAV type approval framework. This framework must evaluate highly complex systems in a transparent and fair way, while restricting innovation as little as possible. In this paper, the requirements, format and implementation of the database are outlined and discussed in the context of the wider system and test process. This reflects understanding gained from a trial database deployment with approximately 70 users.

Keywords:

Automated driving systems, certification, scenarios, safety, simulation

1 Introduction

As highly automated vehicles reach, or near, commercial deployment, new robust but time-efficient approaches for ensuing their safety are required. In the case of features with lower levels of automation, a Lane Keep Assistance (LKA) feature for example, it has typically been possible to ensure safety by conducting lengthy physical trials coupled with a safety argument (predominantly focused on assessing failure modes and system malfunctions). For higher levels of automation, this approach alone is unlikely to be sufficient. Considering all the combinations of road geometry, movements of road users, static objects on and beside the roadway, weather conditions and temporary obstacles such as roadworks, the combined test parameter space is effectively infinite. The test space cannot be completely covered in physical test drives and cannot be documented comprehensively. These factors mean that automated driving systems (ADS) require innovative approaches to verification and validation.

For regulators, the arrival of higher levels of automation also creates a challenge. Regulators have the remit to keep society safe and ensure a fair market, whilst not wanting to hinder technological or

[†] MUSICC is sponsored by the UK Department for Transport. Note that ideas expressed in this paper are those of the authors only.

economic progress. A main tool to achieve this remit is the type approval process – confirmation that a production vehicle meets specified performance standards.

1.1 Scenario testing as part of the solution

For both the development and certification challenges described above, **scenario-based testing** is a promising method for demonstrating the safety of highly automated vehicles [1]. This approach evaluates an ADS using a body of generated scenarios of differing abstraction levels. The authors take the definition of *scenario* from [2] as: '*A scenario describes the temporal development between several scenes in a sequence of scenes. Every scenario starts with an initial scene. Actions & events as well as goals & values may be specified to characterize this temporal development in a scenario'*.

To achieve acceptable test coverage, each ADS needs to be tested against many varied scenarios. The scenario approach can then be applied across a range of testing environments, including simulation [3], vehicle-in-the-loop and proving ground, with each testing environment chosen for its capability to expose particular system weaknesses and with transference of test scenarios between environments desirable. For regulators, scenario testing presents a challenge as the infrastructure and processes to manage this type of testing do not yet exist. An agreed set of scenarios would need to be developed, a consistent language to share them would be needed, and capability to integrate with all types of ADS implementations would be required.

Industry feedback noted in the 2019 MUSICC symposium report [4] suggested that these scenarios cannot be generated from a single source, as the required learnings and scenario variability are distributed throughout the industry. This presents a challenge: a body will need to manage a large number of contributions of variable quality from different organisations. Collaboration between organisations is therefore key. This paper outlines an accessible and flexible scenario database for efficient sharing of scenarios. It is intended to ensure that the burden of generating large sets of test scenarios is minimised, with the database, and associated research activity, also acting as proof-of-concept to explore the opportunities for regulators of using a form of scenario testing as one of their mechanisms for ensuring connected and autonomous vehicle (CAV) safety.

This paper now provides the context to the MUSICC (Multi User Scenario Catalogue for CAVs) project, covers the choice of Scenario Definition Language (SDL), describes the implementation of the database, outlines the test processes that MUSICC allows, examines how MUSICC sits within a wider test and certification framework, and concludes with recommendations for future work.

2 Background and Context

Connected Places Catapult, CPC, is a UK organisation established by the UK government to promote innovation in intelligent mobility and the built environment. CPC operates at the intersection between the private and public sector to tackle complex issues, such as CAV certification, that both involve the introduction of new technology and require input from many varied stakeholders.

MUSICC, led by CPC, is a two year project with the objective of creating a catalogue to store and share a library of test scenarios. While MUSICC is focused on scenarios for highly automated vehicles, it can store a subset of the handover scenarios applicable to partially automated vehicles. MUSICC has a four step approach: (A) Gather stakeholder views on how to address the challenge and determine scenario library requirements; (B) Develop a suitable format and build the scenario library (C) Open database for stakeholders to engage with; D) Use feedback to both improve the system and input into the wider certification process.

The MUSICC system has been released as open source, and a MUSICC database is live in beta test mode (links to the source code and beta test system can be found via [4]). The prototype database is already receiving interest from the automated driving community with 70 registered users from a range of countries. The project has not set out to populate the database but has developed a set of sample scenarios to validate the system and enable stakeholders to evaluate and integrate it with their processes.

MUSICC is proving the concept of using a shared scenario catalogue to certify CAVs. In parallel with this activity, regulators have the responsibility for exploring the level of safety that will have to be achieved, and of choosing the associated scenarios this level of safety will have to be demonstrated over.

2.1 Related projects

The PEGASUS project [5] has worked to create a scenario-based method for verification and validation of autonomous vehicles. In parallel, HEADSTART aims to align testing and validation processes across projects. Other projects which take a scenario based approach include TNO Streetwise [6], Foretellix [7], SAVVY, StreetWise, dRisk and VeriCAV [8]. Crucially, none of these have regulatory applications as their primary use case. CETRAN [9] is involved in developing regulatory tests in Singapore: MUSICC complements this work, which does not contain a scenario database component.

3 Scenario description language

Integrating data and processes from a wide range of stakeholders is important for MUSICC, which made it critical to import and export scenarios in a format that captures all the required information, is easy to use, and has significant industry traction. This meant that defining the format or *scenario description language* (SDL) used for representing scenarios was the focus of the early stages of the project.

The SDL must be capable of representing dynamic events (such as the movements of actors and weather and lighting conditions) and static content (such as the road network and potentially the surrounding infrastructure including vegetation and buildings). It should capture these at the most appropriate level of detail for regulatory testing; the PEGASUS project has defined three levels of abstraction [10]:

- Functional, the most abstract level, where scenarios are specified in plain text. An example functional scenario might simply be “a cut-in on a 3-lane highway”.

- Logical, where scenarios are specified in a machine-readable format, but not all values have fixed values. For example, parameters may allow a range of speeds for the actor vehicles participating in the scenario.
- Concrete, where scenarios are fully defined.

A related question is the extent to which perception systems should be tested as part of regulatory approval, and especially approval tests conducted in simulation. This determines the need to include detailed 3D models of the surroundings within scenarios. Based on views expressed by a range of key stakeholders at a project workshop held in September 2018[2], MUSICC's SDL has the following features:

- Optional storage of scenery, modelled in a standard 3D file format.
- Representation of both logical and concrete scenarios. Storing only concrete scenarios was felt to require far too many scenarios to achieve sufficient coverage.
- Test-time randomisation (to prevent systems from being designed to pass a finite, fixed set of tests), but balance this against the need for repeatable tests.
- Built upon the emerging industry standard format OpenSCENARIO.

3.1 Industry standards

Road networks constitute the major static component of scenarios, and several formats exist for them, including OpenStreetMap and HERE Maps. A format that is well suited to CAV use is OpenDRIVE [11], and a recent Zenzic report suggests that it should be adopted as the road network standard [12].

As well as the road network, a scenario must include dynamic elements. Some public standards for this exist, such as GeoScenario [13], but most industry attention is focusing on OpenSCENARIO[3] [14], the companion format to OpenDRIVE. OpenSCENARIO and OpenDRIVE are both XML-based formats developed by VIRES but being published by the standards body ASAM following industry consultation. Looking further into the future, ASAM are running a Concept project for OpenSCENARIO to develop the next iteration of the language, which is likely to be similar to Foretellix's M-SDL [7] language.

3.2 MUSICC's scenario description language

MUSICC's SDL represents scenarios using three records: an OpenDRIVE, OpenSCENARIO, and MUSICC record (all stored as XML). The MUSICC record stores additional necessary data beyond the OpenX standards: scenario metadata and data to enable parameter stochastics (see Section 5 for details on randomisation of parameters). Part of the metadata relates to Operational Design Domain (ODD) and is discussed in Section 5; other metadata includes the version, revision and update timestamp, a text description of the scenario, the organisation owning the IP, and the abstraction level of the scenario.

MUSICC stores logical scenarios by default; however, functional scenarios can be managed using a tag

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[2] The minutes of this workshop were not published, but are available on request

[3] Connected Places Catapult and HORIBA MIRA are actively involved in OpenSCENARIO development

to link logical scenarios derived from the same functional description. Concrete scenarios can be generated automatically on export, or can be stored directly if desired.

While the MUSICC SDL has been designed with simulation in mind, it is simply a precise, machine readable description of a scenario. This means that it can be used for any type of testing, including hardware in the loop and proving ground tests.

4 Implementation of a regulatory-focused scenario library

This section describes MUSICC from a software engineering perspective. How to integrate the system with systems engineering and type approval processes are discussed in Sections 5, 6, and 7.

4.1 System requirements

Given that the intention is for MUSICC to store all regulatory test scenarios, a key requirement is the ability to search for and export a subset of scenarios appropriate to certification of a particular ADS in a particular territory. This implies support for finding all scenarios that fall within a specified ODD (Section 5 gives details on how this has been implemented).

Other requirements for the database include:

1. Provide easy remote access to scenarios stored in a machine-readable format.
2. Store version history for scenarios.
3. Support scenario management and approvals processes.
4. Provide an easy-to-use API for scenario export, to allow tool integrations.
5. Provide a web-based UI, supporting searches based on ODD, edit, user management, etc.
6. Scale to store a sufficient number of scenarios in a robust way.

One requirement that has not arisen in stakeholder discussions is to have multiple different output formats, e.g. those used by different simulation tools. In general a better outcome for all involved would be to align on a single, standardised scenario format.

Finally, the system should handle change easily, both in scenarios and in the SDL itself. This is critical because understanding of technology is evolving rapidly, and because new scenarios will likely be needed, as evidence from CAV deployment comes to light, and as the operating environment evolves (e.g. new vehicle types, new signage, or new junction styles).

4.2 Existing tools

Many technical solutions exist for the storage and version control of documents (e.g. Microsoft SharePoint) and software (e.g. Git), but these do not meet all the requirements listed above. In particular, there would be no way to enforce storage of scenarios in a homogenous format, and no way to search the repository using ODD-related attributes.

A non-technical requirement, clearly articulated by the project’s sponsors, was that the system should be freely available for use by all regulators around the globe, rather than being subject to commercial or restrictive licencing. While some organisations and projects are developing tools specifically aimed at storing and managing CAV test scenarios (as mentioned in Section 2), these are proprietary and/or have restricted access, which makes them inappropriate for regulatory use.

4.3 Proof-of-concept system

The CPC has built a proof-of-concept system which meets the requirements detailed above. The system has been created using open source languages and tools, and Figure 1 shows a screenshot of the main page of the web application. MUSICC stores scenarios and application data in a relational database (Postgres), and the web interface and application logic are built in Python using the Django framework. This system has been released as open source, see https://gitlab.com/connected-places-catapult/musicc.

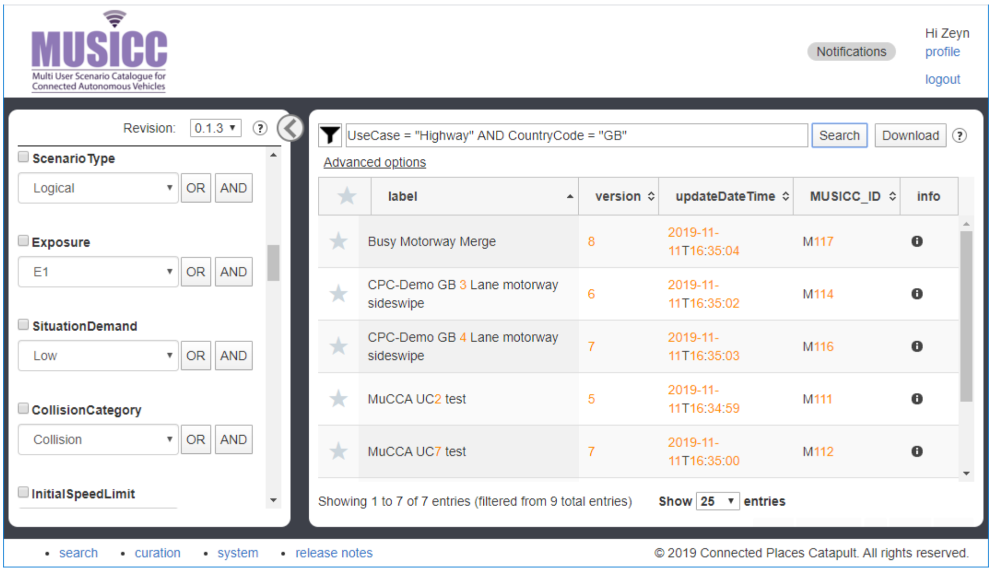

Figure 1 - Screenshot of MUSICC's main page

Features include a view of search results with selectable columns and customisable ordering, and the ability to download the search results as either logical or concrete scenarios. A "scenario detail" view shows the XML for all three component files, with the ability to comment on and favourite the scenario, display thumbnails or videos of the scenario, and view the scenario's history. As well as storing 3D model files (as OpenSceneGraph or FBX), arbitrary support files can be stored with scenarios, allowing files needed by particular tools to be managed.

The system has been designed to cope easily with changes to the *revision* of the SDL (i.e. the format of the MUSICC, OpenDRIVE, and OpenSCENARIO records). New revisions can be supported without any code changes, as the user interface is dynamically built using the XML schema for the current revision to create the search fields. The schemas for each revision are stored, with full history, within the database enabling traceability. Highly automated tooling is also provided to help migrate existing scenarios to a new revision.

Organisations can also manage a local instance of MUSICC, with the ability store private scenarios and to synchronize regulatory scenarios from the CPC instance. A Docker install makes this straightforward.

4.4 Management of scenarios for regulation

We anticipate that many regulations may exist for CAV certification, covering different countries, approval dates, and ADS with different ODDs. To identify which scenarios are part of which regulations, MUSICC can tag each scenario with a unique identifier for each of the regulations it is used in. To allow for minor changes in the scenario set without needing legislation, we recommend a version number suffix is appended to tags. For example, if the original scenario set was tagged with “LKA_Reg-23-05v1.0”, the revised set could use “LKA_Reg-23-05v1.1”.

For regulators to proactively manage scenarios, several levels of supervision will be needed. At the top level, a knowledgeable yet independent body should decide which functional scenarios should be included in regulations. For example, if the UNECE were to adopt MUSICC, this body could be an expert group (“GR”) of Working Party 29 (the World Forum for Harmonization of Vehicle Regulations).

At the level below this, a curator role is needed, embodying expertise in verification of CAVs, simulation and scenario formats. The curator would have the responsibility for ensuring that appropriate logical scenarios are present in the database for every functional scenario. They would have to review, quality-check and suggest any needed amendments to new scenarios submitted to the system, and finally they would have responsibility for ensuring that scenarios are updated appropriately as critical new test cases come to light, new knowledge and best practices emerge, and as scenario formats evolve or road infrastructure and traffic patterns change. The MUSICC system has workflows built in to support all these tasks, for example requiring two different curators to approve externally-submitted scenarios.

Finally, low-level support will be required for database administration and bug-fixes and enhancements to the system software itself.

5 Test process

5.1 Selecting tests using ODD metadata

Scenarios in MUSICC are labelled with metadata which can be searched using a query language. For selecting regulatory tests, the key items are:

- An identifier for any regulations which reference this scenario (as discussed in section 4.4).
- A set of variables used to define the ODD. It is essential to be able to identify scenarios which are relevant to the application of the ADS under test.

At present, the ODD is represented using nine core variables. These cover information about the location (country code, real-world location if applicable), features of the road network (speed limit, number of lanes), environmental conditions (weather, time of day), the intended ego vehicle type (e.g. M1 – passenger car), and general properties of the traffic flow (traffic density and average speed). One or more values can be assigned to each of these, which increases the expressive power. Possible future enhancements to the ODD metadata include:

- Changing the values stored to comply with emerging standards, such as BSI PAS 1883.

- Adopting a hierarchical structure, to allow more detail to be defined where needed (and not requiring it to be specified otherwise).
- Allowing searches based on a stored ODD specification, tied to a single version of the ODD description format, to reduce the risk of some types of error when specifying an ODD.

5.2 Randomise scenarios on export

MUSICC contains functionality to randomly vary parameter values within a scenario. This has two main advantages: it reduces the number of scenarios which need to be stored and means that ADS developers cannot know the exact specification of the test in advance. The distribution for each stochastic parameter (uniform or Gaussian, with appropriate arguments) is stored in XML within the MUSICC record.

When a randomised download is requested, the system will automatically assign a value to parameters according to the specified stochastics. Alternatively, the MUSICC XML record itself can be downloaded, which can be used as an input to sophisticated parameter selection tools (e.g. tools to automatically identify edge/corner cases). Scenarios can then be executed to evaluate the behaviour of the ADS.

5.3 Score outcomes using transparent, objective measures

Regulatory testing needs to be transparent, fair, and effective at ensuring the safety of the public. For evaluating scenario-based tests, it also needs to be highly scalable: millions of scenarios may need to be tested. These requirements point towards an automated evaluation process.

A separate paper sets out our proposed approach to scoring scenarios in MUSICC [15]. This approach evaluates the following properties of an ADS:

- Whether it causes collisions, according to the principles set out in [16].
- Its ability to avoid collisions caused by others.
- Compliance with traffic laws.
- Whether adequate safety margins are left.
- Confusing or inconsiderate behaviour.

Tests for these properties may be prescriptive (define acceptable outcomes in each concrete scenario) or risk-based (define acceptable outcomes statistically across a test set). Reference [15] also discusses how an overall result can be reached based on these tests. It is anticipated that test definitions, defined using a programming language, will be stored alongside the scenarios: a library of common test definitions will assist with this. In the future, it may be possible to generalise the approach to produce a global set of tests (conceptually similar to the digital highway code proposed by [17]).

6 Embedding MUSICC into verification, validation and certification processes

Scenario-based testing is a requirement for CAV verification and validation, and MUSICC fulfils a clear and important need in managing the resulting large, and complex, scenario sets. However, MUSICC is designed for use within a wider verification and validation framework, so its adoption and success is dependent on integration with the associated processes and workflows. Crucially the scenario sets must be traceable to deployment environments with evidence of adequate coverage.

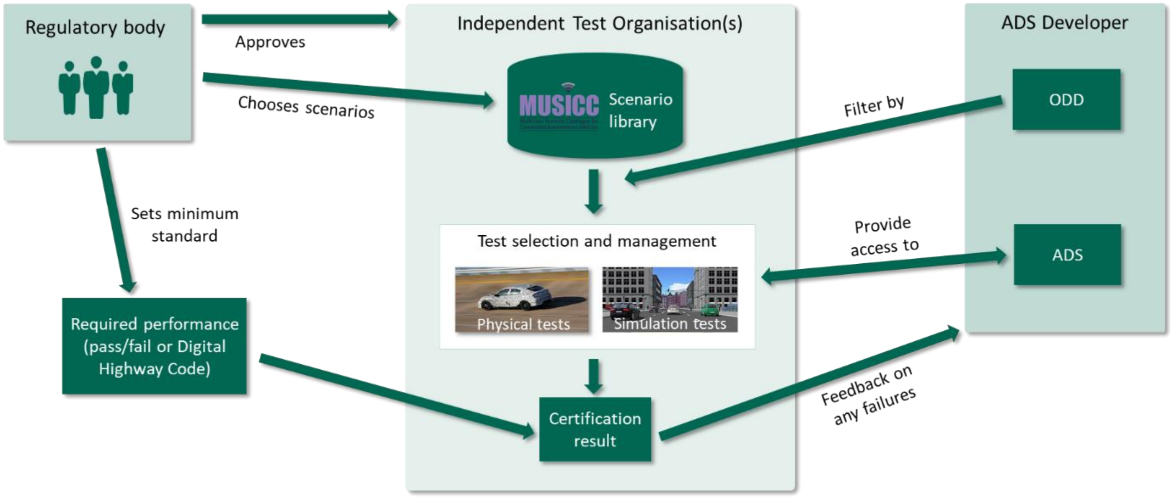

Figure 2 – Illustration of MUSICC in the context of a certification process

The primary use case for MUSICC is facilitating regulators in conducting certification activities, as illustrated in Figure 2. These certification scenarios may also be made available directly to industry for further contributions and for testing during the engineering lifecycle. This results in two different workflows in which MUSICC may be used, as summarised in the following two subsections.

6.1 *Systems engineering processes*

Automated driving systems adapt their function and performance to the environment and driving situation. System requirements must therefore map the behavioural requirements of the feature to the environmental requirements of the ODD. In a systems engineering workflow, the test scenarios must be traceable to these system requirements, and it must be demonstrated that adequate performance and test coverage has been achieved. MUSICC supports local private instances of the scenario database allowing developers to manage their internal scenarios and certification scenarios with the same tools.

Robust methods to systematically parameterise a complete set of scenarios are required, and are being actively developed, but have not yet been formally standardised or widely adopted. The SAVVY and VeriCAV research programmes [8] introduced the concept of intended and unintended parameters.

Intended parameters are, by design, expected to directly affect the system response or behaviour, and can be directly derived from the system requirements. Unintended parameters should not affect the system response or behaviour, by design, but can reasonably be foreseen to have a challenging or degrading effect. For example, the performance of a camera-based perception system will likely be affected by the presence of heavy rain. These parameters may be derived from the hazard analysis associated with functional safety and SOTIF (safety of the intended functionality) activities.

Test coverage of intended and unintended parameters is prioritised as these are directly linked to the system requirements or known hazards. Their values may be selected to target specific weaknesses of the system (identified from prior knowledge or the test process itself). For each scenario there will be other, “residual”, scenario parameters that occur within the ODD but are not expected to alter the system’s behaviour. These can be set to random values to enhance test coverage.

6.2 *Certification processes*

In a certification workflow the scenarios must be independent of the specific design or implementation of a given system-under-test. Furthermore, the detailed systems requirements are not known as they were assumed to be in the systems engineering lifecycle.

In theory a generic set of scenarios may be derived from common environmental and behavioural requirements that exist for a user type within an ODD. A major challenge of this approach is that even a simple ODD can give rise to very varied scenarios, some of which may not be easily foreseen. Multiple complementary methods are likely to be needed to maximise confidence in these definitions, such as reviewing data from field trials and accident databases, as discussed in [18].

A further challenge is that there is no universal definition of acceptable behaviour, which would be required to derive intended and unintended parameters. However, this could be partially resolved by applying national regulations and codes of practice, sometimes referred to as a Digital Highway Code.

An alternative approach proposed by NHTSA and Waymo [19] is to define a standard set of behavioural competencies. These define a minimum set of driving capabilities needed to achieve automated operation. These competencies can be treated like high level use cases and used to derive generic test scenarios and parameters. This approach can be used in conjunction with the ODD to further bound the scenarios and parameters of relevance based on the functionality of a given system.

7 Pathway to a certification process

The MUSICC project has created a live online scenario catalogue, and, through an active beta test programme, is building a body of evidence showing the value of this system for certification testing. MUSICC has defined a scenario description language that builds on OpenDRIVE and OpenSCENARIO by supporting parameter randomisation and metadata. The system supports ODD-focused search and download of scenarios, and has robust approval and version management workflows as appropriate to a regulatory tool. Finally, we’ve started work on representing and applying pass/fail criteria, which are needed to analyse and collate data from individual scenario tests to arrive at a certification result.

MUSICC has the potential to be a key component of the future CAV certification process, though some significant challenges remain. Critically, for virtual testing to play a major role, some form of accreditation for the simulation tools used is necessary. This becomes even more important when perception tests are performed in simulation, meaning the sensor and environment models also need to be validated. Further work to improve coverage in certification testing would be to probe fault injection (for example, handling a sensor failure), to include connectivity (V2V and V2I) aspects, and to allow other traffic agents to behave intelligently within scenarios (for example, controlled by AI systems). These are difficult given the need to work with all ADS architectures and to use known, repeatable tests.

Looking beyond the test process, gathering or creating the right set of scenarios is a challenge. This is critical because these scenarios underpin the safety argument and a wide range of expertise and data will be needed to create them. It is not yet clear whether ADS developers should have access to all logical scenarios in MUSICC. Keeping a set purely for performance assessment would reduce the risk of systems being designed to the test, but it may be difficult to cover the test space in both the training and assessment sets without duplication. If this approach is adopted, the mechanism for giving feedback on failures will need careful design.

Managing ODDs is an area regulators may want to consider: limits on permissible ODDs could help ensure efficiency and safety at a network level, as well as helping consumer understanding. To aid this and other assurance tools (including MUSICC), a standardised ODD representation language is needed.

Another key task that falls to regulators, albeit with significant community input, is to define the minimum safety standards and express these in precise terms. Finally, some type approval requirements will not be covered by scenario-based tests – including the need to use robust safety engineering processes, ensure component redundancy, and perform white-box tests – so regulations and processes need to be defined to cover those. These may include manufacturer audits and declarations.

Given that many regulators would prefer a test process that can be carried out independently, as opposed to using the OEM's facilities, part of the challenge is collaborative: virtual testing of an ADS requires interfacing and modelling of a large number of systems, potentially from a variety of suppliers. Each of these systems represents valuable IP, so developing the legal and technical frameworks to connect them together will require commitment from all parties. Further, while significant resources will be required to identify high-quality scenarios, we believe there is a requirement for at least some certification scenarios to be freely available to all international regulators and technology developers.

Safety assurance for CAVs will not end with type approval, given regular over-the-air (OTA) updates are likely for ADS, and MUSICC can assist by enabling efficient regression testing of OTA updates over many scenarios. Data gathered from the in-service fleet can be used for "continuous certification", or to identify new critical scenarios. Finally, on an individual vehicle level, through-life periodic technical inspections will be needed to ensure degradation has not impacted the performance of the ADS.

There is a lot of work to be done in this area, but MUSICC has an important role to play in allowing stakeholders to gain hands-on experience of some of the methods needed, and thereby inform the wider landscape. The community is gaining awareness of the importance of a robust approval process for CAVs, and this has helped drive many new initiatives including standardisation efforts and collaborative, cross-cutting projects focused on assurance.

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