Interoperable simulation across CAM Testbed UK

ZENZIC
SELF-DRIVING REVOLUTION

CREATING A SEAMLESS
CAM TESTBED UK

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Contents

Foreword

Safety is at the heart of connected and automated mobility (CAM). Strong evidence of safety will be key to the deployment of self-driving vehicles at scale, unlocking manifold societal and economic benefits. The challenge has always been to put self-driving vehicles through their paces in a way which replicates enough of the day-to-day and edge case scenarios that we see on our roads. Encountering enough of those edge cases on physical roads, in a timely, cost-effective and safe manner, is unrealistic. Therefore, virtual validation and verification in a simulated environment is critical to the success of CAM.

Simulation tools are widely available today and there is a deep level of expertise across the UK and globally. There are many leading players and disruptors who are bringing simulation toolsets to the market to support the safe deployment of CAM. In fact, there is no shortage of choice, when it comes to CAM developers looking for support to test and develop in a virtual platform. This does however present a challenge. Many simulation packages can deliver simulation capabilities in specific areas or focus on only a portion of the scenarios needed to ensure the robust performance of self-driving vehicles on the road. When a company developing CAM products or services wants to take a comprehensive approach to virtual testing, where do they go, what do they choose? This is the challenge that interoperable simulation is addressing.

Across the CAM Testbed UK facilities, a CAM developer can find many of the aspects of virtual testing they may require. However, if a specific testing scenario requires capabilities at those different locations to deliver, how does the customer access them? Should they travel between sites, carrying out small parts of the tests then piece together the results separately? For each location is there a need to re-integrate into a new toolchain to run the tests? These are just two of the challenges facing developers in the UK and across the globe.

CAM Testbed UK, under its interoperability programme, has delivered a novel proof of concept (PoC) architecture which shows how, at a single location, customers can access multiple capabilities across geographically distanced sites, in a single test scenario. This allows customers to run more complete and comprehensive testing without the need for multiple integration activities or a piecemeal approach to a single test.

In addition, the architecture enables seamless movement between facilities to carry out similar tests in different simulation contexts. For example, an organisation can expose their system to the same scenarios in different simulators, with minimal re-integration, affording a richer understanding of system performance across different simulation setups. This is all enabled through the use of interoperable models and simulation approaches.

There is still more work to be done, but the foundations of a customer-focussed interoperable approach to simulation have been laid. CAM Testbed UK is leading the way towards a more holistic, simplified approach to accessing and undertaking virtual validation and verification that supports CAM developers and informs Government regulation.

This report takes you through the technical and operational considerations in delivering this PoC and calls on the CAM community to continue to work together to ensure that CAM is delivered safer and quicker than any one of us can do individually.

Mark Cracknell

Head of CAM, Zenzic

Executive summary

This project explored the feasibility of interoperable simulation across CAM Testbed UK, demonstrating CAM Testbed UK can deliver a world-class solution to the challenge of providing an interoperable virtual testing environment. This has been accomplished through two streams of work:

1. **Interoperable simulation proof of concept demonstrator** – Delivery of a PoC framework and architecture, laying foundations for the creation of a comprehensive interoperable simulation environment for CAM Testbed UK. Demonstration of this framework with a real-world customer, showcasing its real-world applicability.
2. **Role of interoperable simulation for CAM development** – Establishment of a longer-term view to provide an extensible framework for future operational deployment of interoperable simulation services across CAM Testbed UK, accomplished through industry stakeholder engagement and review processes.

The processes for the development, evaluation and certification of connected and automated mobility (CAM) technologies are immature. However, the use of virtual environments for each of these processes is likely to play a critical role. Simulation is a tool that offers developers routes to attack this problem by cost-effectively providing greater speed and flexibility of approach. This must be tempered against the critical need for simulation facilities to achieve the required level of fidelity and validity to generate useful and practical outcomes for their users. **Interoperable simulation** enables connections between independent simulation facilities and other virtual or physical testing platforms to achieve **broader and deeper testing capabilities** and **open simulation approaches to a wider market**.

The PoC demonstrator framework was collaboratively delivered between Millbrook (Millbrook-Culham Urban Testbed), WMG (Midlands Future Mobility) and Smart Mobility Living Lab: London (SMLL). The framework consists of a range of industrial grade simulation capabilities contributed by each of the facilities, these being the building blocks for the integrated, distributed, and interoperable simulated environment across the three sites.

These capabilities were integrated using a data-distribution service (DDS) data bus architecture as the middleware, providing several unique features to the integrated simulation environment including flexibility, modularity, and expandability, in addition to real-time capability and quality of services (QoS).

A self-driving software stack (ASLAN) from StreetDrone (the project customer), was integrated into the framework, to test its various automated driving (AD) functions. Five different scenario-examples across the SMLL route were defined and implemented in a scenario description language (SDL). The SDL files were uploaded into WMG's National Scenario Database (NSDB), with remote access to the scenarios at Millbrook. The capability of including live data from an intelligent traffic management system (ITMS) into the distributed framework was also demonstrated by running a real-time co-simulation between Millbrook and SMLL, fed with live

traffic signals from the SMLL route in London. In addition, a "stand alone" demonstration at WMG's 3xD simulator showcased the transferability and flexibility of the framework as the same simulation architecture was integrated into a different simulator.

Demonstrations across the three sites showcased the various unique features and capabilities of the framework, whilst also confirming the coverage of all three options of simulation interoperability: **model interoperability, simulation interoperability** and **distributed simulation**. This has seamlessly afforded StreetDrone deeper insights into their system's performance across different simulation contexts, as well as invaluable learnings and expertise for the whole CAM Testbed UK ecosystem through the highly collaborative delivery of a technically rigorous framework. These outcomes are beyond the capabilities that any one CAM Testbed UK facility can offer, demonstrating the multiplication of benefits that arises from an interoperable approach.

The simulation results demonstrated world-class technical capabilities and confirmed that CAM Testbed UK can deliver an integrated, flexible and expandable solution to cover a wide range of large-scale simulation tasks, scenarios and use-cases, outperforming any other all-inclusive simulation tool. This presents a new level of collective simulation capacities by CAM Testbed UK that can be used for development, test and validation of CAM products and services.

Although demonstrative of CAM Testbed UK's ability to establish a world-class framework, the PoC must be accompanied by carefully considered recommendations for future operationalisation and expansion for interoperable simulation to be a success. The second workstream "Open simulation framework" has provided said recommendations.

The complex coordinated interactions that constitute interoperable simulation open new possibilities for CAM testing, trialling and development that may help tackle some of the more challenging elements in this field. Particular opportunities for interoperable simulation were identified in:

- enabling a greater depth and variety of connected and automated vehicle (CAV) safety testing;
- standardised CAV evaluations across a library of test scenarios;
- improving the cost effectiveness of CAV development;
- improving translation between virtual and physical tests of CAVs;
- enabling regulatory tests of CAV performance;
- opening the possibilities for interoperability with customers and/or collaborators beyond CAM Testbed UK.

However, there is much work to do to make interoperable simulation across CAM Testbed UK a success. Simulations must achieve the required levels of fidelity and validity to deliver credible results while standards of data sharing and connectivity between simulation components must be achieved and maintained with minimal latency to ensure successful outcomes. Cyber security risks must be mitigated without harming the compatibility of simulations with industry standard systems to ensure appeal to the widest range of potential customers. Intellectual property rights must also be respected, ensuring data exchanges between simulation components/facilities occur under carefully managed protocols.

Recommendations identified that:

- the operating model for CAM Testbed UK interoperable simulation facilities should be to collaborate loosely (rather than be coordinated by a dedicated 'front door' organisation);
- activities should be guided and coordinated by a strategic interoperable simulation community group;
- this group would set out the strategic plan for interoperable simulation within CAM Testbed UK and ensure cooperation and alignment between its member facilities;
- marketing must attract customers with clear and coherent messaging about what interoperable simulation can achieve and how CAM Testbed UK facilities collaborate seamlessly in its delivery;
- additional PoC demonstrators would extend the interoperable simulation capabilities of CAM Testbed UK and help to generate interest in the approach.

In summary, this project has proved CAM Testbed UK can deliver a truly world-leading interoperable simulation framework, demonstrating the requisite expertise and collaboration required. The project proves interoperable simulation brings significant added value and benefits for the customer, reducing integration time, effort and costs whilst providing a seamless way to test and develop CAM systems across a broader and deeper set of simulation capabilities.

The comprehensive stakeholder engagement and review process has set a clear path for future development and expansion, informed by experts across the sector. This path details a clear, community-led approach to refining and expanding the framework towards a compelling operational offering of increased global significance. This expanded and flexible capability will generate collaborative opportunities for CAM Testbed UK, whilst providing CAM developers and organisations a truly comprehensive and seamless testing capability.

Stream 1: Interoperable simulation proof of concept demonstrator

Dr Amir Soltani

Summary

CAM Testbed UK is a comprehensive, collaborative, and interoperable CAM test and development ecosystem being developed under the Zenzic testbed programme, as outlined in the *UK Connected and Automated Mobility Roadmap to 2030* (Zenzic, 2021). It is providing testing facilities which can be used by clients to test their products and services across a wide range of CAM use cases. To accelerate products to market and generate the social and economic benefits they promise, there is a need not only for highly interoperable physical facilities but also a complementary simulation environment.

During Phase 1 of this project, a feasibility study was conducted to understand the capabilities of each testbed within CAM Testbed UK. As a follow on from Phase 1, the proof of concept (PoC) demonstrator (Phase 2) was a collaborative delivery between three nominated testbed partners, namely Millbrook (part of Millbrook-Culham Urban Testbed), WMG (part of Midlands Future Mobility) and Smart Mobility Living Lab: London (SMLL), who brought specific capabilities. Millbrook, as the Systems Integrator for Phase 2, was also responsible for the delivery of the integrated simulation environment and the project demonstrators.

As a PoC and to demonstrate the technical challenges, capabilities and benefits of the proposed solution, an integrated, distributed, and interoperable simulated environment has been designed, developed, and implemented across the three testbed partners, using a range of industrial grade commercial-off-the-shelf (COTS) simulation software and tools. Instead of traditional point-to-point (ad-hoc) integration, the simulation tools have been integrated based on a data bus architecture, using data-distribution service (DDS) technology as the middleware, which provided several unique features to the integrated simulation environment including flexibility, modularity, and expandability, in addition to real-time capability and quality of services (QoS).

A self-driving software stack (ASLAN) from StreetDrone (as the project customer), was integrated within the simulation environment, to test its various automated driving (AD) functions. Five different scenario-examples across the SMLL route were defined and implemented in a scenario description language (SDL). The SDL files were uploaded into WMG's National Scenario Database (NSDB), with remote access to the scenarios at Millbrook. The capability of including traffic data from an intelligent traffic management system (ITMS) into the distributed simulation environment has also been demonstrated by running a real-time co-simulation between Millbrook and SMLL, fed with traffic signals from SMLL in London.

As a result of joint efforts between the testbed partners, the outcomes of the project were successfully demonstrated at Millbrook, WMG (MFM) and SMLL, which presented various unique features and capabilities of the integrated simulation environment, and more specifically confirmed the coverage of all three options of simulation interoperability. These were: model interoperability, simulation interoperability and distributed simulation. This has brought added value and benefits to the customer, and the whole CAM testbed UK ecosystem, which are beyond the capabilities that any one CAM Testbed UK facility can offer.

1 | Introduction

The introduction of connected and automated vehicle (CAV) technologies has enabled a new disruptive set of products, applications, and services, known as connected and automated mobility (CAM). Due to the considerable costs and times involved in setting up real experiments, especially for large numbers of test scenarios, modelling and simulation (M&S) has become an indispensable part of all research, development, test, and validation of CAM technology and products.

A wide range of (all-inclusive) advanced simulation software, tools and solutions are available in the market, ranging from free open-source software and packages to expensive commercial-off-the-shelf (COTS) products from various global vendors. These modelling and simulation packages are being used extensively in universities and industry for various simulation tasks and applications. The main limitation of all the existing all-inclusive packages is the fact that they are generally good in one or a few M&S domains (such as vehicle, sensor, road, terrain, traffic, and so on) but have limitations on interoperability, flexibility and scalability. By increasing the complexity and the number of functionalities of CAM systems and products, and also the requirements of running hundreds of thousands of scenario variations, it becomes apparent that no single simulation tool is capable of running large scale complex simulation with enough levels of flexibility, fidelity and comprehensiveness, especially for real-time applications and production level Verification and Validation (V&V).

Interoperable simulation seems a promising alternative solution to address some of the current M&S challenges, as briefly highlighted before. Although the topic of simulation interoperability is a relatively new concept in the automotive industry, especially in CAM domains, the benefits and advantages of simulation interoperability, especially for large scale M&S tasks, has been identified and acknowledged in the defence industry for many years (Schmidt, White and Gill, 2014). Interoperability is referring to the capabilities of exchanging the simulation models, simulation tasks or to simulate in a distributed environment.

The goal of this project is to propose and examine a range of novel solutions for simulation interoperability within CAM Testbed UK, and to demonstrate new interoperable modelling and simulation capabilities, which are beyond the capacity of any single CAM Testbed UK facility. The project aimed to provide potential customers a wide range of seamless, integrated and interoperable modelling and simulation toolchains, to enable them to test and validate their CAM products and services in large-scale scenarios. This work proposes a novel approach to efficiently integrating various simulation tools, by demonstrating various interoperability options, including:

- Model interoperability,
- Simulation interoperability and
- Distributed simulation.

As a PoC, delivered in collaboration with three leading CAM Testbed UK partners, namely Millbrook (Millbrook-Culham Urban Testbed), WMG (Midlands Future Mobility) and SMLL, an integrated, distributed and interoperable simulated environment was designed, developed and implemented, using a range of industrial grade commercial-off-the-shelf (COTS) simulation software tools including rFpro (rFpro, 2021), PTV Vissim (PTV Vissim, 2020), IPG CarMaker (IPG Automotive, 2021), Claytex (Claytex, 2021b), TRL SCOOT® (TRL Software, 2021) and open source traffic simulation software SUMO (SUMO, 2021).

The first half of this report is organised as follows. Section 2 presents an overview of the project background and introduces the testbed partners. Section 3 presents a general technical background and description of the project. Section 4 explains the technical specifications of the proposed interoperable simulation solutions that were applied and/or developed in this project. Section 5 presents the tasks and achievements of the project towards the PoC build overall and specifically at each testbed partner (Millbrook, MFM, and SMLL). Section 6 discusses the project results and challenges. Section 7 proposes future activities and next steps of this project and beyond.

2 | Project summary

2.1 Project background

About Zenzic

Zenzic brings together government, academia, innovators, and developers of intelligent mobility solutions in a collaborative partnership. It facilitates and supports the acceleration of the UK's emerging connected and automated mobility sector within the global transport ecosystem with resources to enable profitable growth.

About CAM Testbed UK

CAM Testbed UK is a comprehensive and integrated CAM test and development ecosystem developed under the Zenzic testbed programme. It provides testing facilities which can be used by clients to test their products and services across a wide range of use cases. To accelerate products to market and generate the social and economic benefits they promise, there is a need not only for highly interoperable physical facilities but also a complementary virtual environment.

So–called "digital twins" are being developed for each of the CAM Testbed UK facilities. These are being used in models and simulation applications by each of the testbeds. However, there is little interoperability between them and, where the data or the application is proprietary, this issue is exacerbated. There is a requirement to research and demonstrate how the UK's CAM testbeds can link proprietary systems to create interoperable distributed simulations, whilst at the same time protecting intellectual property.

About Millbrook (Millbrook-Culham Urban Testbed)

Millbrook is the lead partner in the Millbrook-Culham urban testbed– winners of the Meridian 2 CAV testbed competition in 2017, and as part of that testbed investment award, have procured, installed, commissioned and operated a comprehensive suite of simulation assets and toolchains to serve the CAM sector.

Millbrook has specified, built and commissioned a unique suite of simulation as part of the testbed. The Millbrook Simulation Environment is a comprehensive integrated XiL (X in the Loop) ecosystem, including a wide range of latest software, hardware, toolchains and infrastructure. As well as support to conventional vehicle programme development, it is capable of Modelling, Design, Development, Test and Validation of CAM technologies.

Utilising Millbrook's high-speed fibre and 5G private network, and a modular simulation architecture, Millbrook provides a flexible connected environment, to cover offline, real-time, and Hardware in the Loop simulations across the business, including real-world correlation, test and validation of subsystems and full vehicles.

The suite offers a bespoke capability to help our customers develop, test and validate in a virtual and blended controlled, secure environment.

The design and implementation of this integrated simulation environment has evolved beyond the central Driver in the Loop simulator as the first element to be installed in 2018. This is now working with a wide range of professional Software, including IPG, VI-Grade Products, rFpro, Traffic Modelling (SUMO and AIMSUN), Sensor Modelling, and communications and their integration, via complex and internally developed interfaces, APIs (C++, C#, Python, Matlab, Simulink), and middleware. The architecture is now reaching out across the business to other test laboratories at Millbrook, such as those in the propulsion centre, starting to realise a much wider “X in the loop” capability in the transition from internal combustion to electric vehicles of the future.

Future planning and concepts include working with open standards (such as OpenDRIVE, OpenSCENARIO, OpenCRG, OSI), blended simulation, with virtual and mixed realities, and wider interoperability with remote customers and test sites.

About WMG (MFM)

WMG is an academic department at the University of Warwick and is the leading international role model for successful collaboration between academia and the public and private sectors, driving innovation in science, technology and engineering, to develop the brightest ideas and talent that will shape our future.

Intelligent vehicles are set to transform the UK economy and WMG are considered a centre of excellence for connected and autonomous vehicle research. WMG’s multidisciplinary approach, including cooperative driving systems, connectivity, human factors, verification and validation, and simulation and emulation enables a full understanding of the practical applications that will help shape the future of transport mobility.

WMG has led the Midlands Future Mobility (MFM) consortium. MFM brings together leading organisations from the automotive, transport, communications, infrastructure and research sectors in creating an extensive connected platform for the development of future CAM solutions. The MFM route offers a unique combination of campus (mini-city), urban, rural and highways roads (200+ miles) on which trials can be supported. The University of Warwick Campus as a bustling mini-city is open for CAM Trials. WMG’s simulation capabilities support businesses in CAM and communications solutions development, from research and development through to cost-effective ‘right-first-time’ prototyping. Customers benefit through access to Local Authorities, Highways Agencies and expertise from both Industry and Academia for guidance and support in public road trialling and wider Research and Development activities. Customers can access support for trials from Safety Case development to the MFM Vehicle Centre (vehicle storage, preparation and Electric Vehicle (EV) charging facilities), autonomous vehicle platforms for customer V2X and modular CAM feature trialling. The MFM Data Exchange and Visualisation capability maps, stores and selectively shares testbed trial data through an online portal. The MFM Data Hub also provides access to data simulation features, allowing you to plan and review trials along the MFM testbed.

About SMLL

Smart Mobility Living Lab (SMLL) is a London-based real-world connected environment for testing and developing future transport and mobility solutions. It is the world's most advanced urban testbed of its kind with the sole purpose of accelerating the creation of mobility solutions that are clean, efficient, safe, reliable and convenient for everyone using public and private roads in London, to develop and validate new mobility and transport technologies.

The locations of the Royal Borough of Greenwich and Queen Elizabeth Olympic Park in Stratford provide a complex uncontrolled testing environment, interacting with live traffic and other road users. The testbed is designed to demonstrate and evaluate the use, performance, environmental impact, safety and benefits of connected and automated mobility technology and future transport services.

London is the ultimate proving ground: Being Europe's only mega-city, its challenging layout and transport systems are representative of most features found in other towns and cities. It was selected to be home to the SMLL on the basis that if it works in London, then it can be applied to almost any other urban environment.

On a practical level, SMLL services are based around the three integrated pillars of Test, Simulate and Innovate, with a full range of transport technical consultancy provided by TRL, DG Cities and the London Legacy Development Corporation (LLDC). Alongside testing and trialling, SMLL facilitates a community of large corporations and SMEs with an aim to stimulate innovative collaborative R&D projects within the future mobility sectors. SMLL also provides a simulated environment to complement its real-world testing so that customers can begin to extend testing within a virtual environment.

2.2 Phase 1: Initial feasibility study

Millbrook was a full partner in the running of the phase 1 part of the project, to understand the capabilities of each of the testbeds, review the commonalities and shared areas, and also to project forwards a requirement for the operation of phase 2 Stream 1 – a PoC. Through a series of facilitated workshops, Millbrook contributed resource and expertise to work with the project manager to disclose, organise, and characterise the Millbrook environment capabilities. Millbrook took the lead in capability accumulation and presentation, suggested areas of commonality, and though a series of face-to-face virtual meetings, examined the other testbed systems and interfaces. From this, suggestions were made to Zenzic as to the likely framework of the following phase. A summary of the study was documented, summarising the CAM Testbed UK capabilities (as a separate document, not included in this report), along with a proposal for the future plan – all of the material proposed has now been formed into Phase 2 of this project.

2.3 Phase 2: PoC demonstrator for interoperable simulation capability

The objective of the second phase of the project (this project) was to build a PoC demonstrator and develop recommendations for further work. This was a collaborative delivery between three selected testbeds who brought specific capabilities as defined in the outline architecture in the supplier summary brief.

This project aims to:

- demonstrate that CAM Testbed UK can provide a world class solution to the challenge of providing an interoperable virtual testing environment
- lay PoC foundations for a framework and architecture for the creation of a comprehensive interoperable simulation environment for CAM Testbed UK
- assess the extent to which CAM Testbed UK can prove costs can be reduced and efficiency increased by optimising software purchase/maintenance
- demonstrate that technology providers can protect IP whilst still being able to interact with the simulation
- provide UK Government with additional understanding of how best to integrate different simulations to support rapid development of future regulation (i.e. complement the CAV PASS and Department for Transport activities)
- publish and promote results and findings to a cross-sector international audience, building on previous work in safety, cyber and geodata.

The scope of the project was to:

- finalise the requirement specification for the PoC demonstration
- prepare the architecture and interface design for the PoC demonstrator
- prepare the integration platform to use the individual CAM Testbed UK tools/capabilities
- engage and on-board a significant “customer” who would participate in the PoC demonstrator
- integrate the with the customer testing requirements and testing of the PoC demonstrator
- design an extensible framework, propose options for exploitation and develop recommendations for further work
- showcase the PoC at a demonstration event.

This project has two key streams of delivery:

- **Stream 1 – Interoperable simulation PoC demonstrator**
- **Stream 2 – Role of interoperable simulation for CAM development**

Stream 1: Interoperable simulation PoC demonstrator

- Focussed on producing a compelling PoC demonstration of interoperable simulation
- Using a focussed subset of CAM Testbed UK partners and capabilities to prove the concept
- Deliver an offline test capability as a demonstration of the "art of the possible"
- Include a single customer/user to demonstrate real-world applicability

Millbrook acted as the project lead and covered the technical and management tasks. The project Gantt chart is provided in Appendix A. To deliver the project, Millbrook worked with the following CAM Testbed UK partners (including Millbrook, as a testbed partner):

- **Millbrook Proving Ground (Millbrook-Culham Urban Testbed)**
- **Smart Mobility Living Lab: London (SMLL)**
- **WMG (Midlands Future Mobility)**

Millbrook engaged subcontracted partners to assist the programme, bringing their own areas of expertise:

1. **KAN Engineering Ltd**[1]: Technical lead on the design, development, and implementation of the PoC (Stream 1)
2. **Reed Mobility**[2]: Development of the long-term plan and recommendations for further work (Stream 2)

The following partners also provided technical support and advice to the project team.

1. **IPG**: Vehicle model, ASLAN/IPG interface/plugin
2. **PTV**: 4 months free license of Vissim traffic simulation software
3. **RTI**: 6 months free license of DDS middleware software (DDS Connext®), and technical support on the design and implementation of APIs.
4. **NISSAN**: Nissan eNV200 vehicle data
5. **Claytex**: Sensor model integration support

[1] https://kanengineering.co.uk/
[2] https://www.reed-mobility.co.uk/

Stream 2: Role of interoperable simulation for CAM development

- Takes a longer-term view to identify exploitation pathways
- Develop and propose an extensible framework for future operational deployment across CAM Testbed UK
- Inform specific demonstrator architecture but take a more holistic view to interoperable simulation as a long term objective
- Consultation across all parties in CAM Testbed UK to ensure wide applicability
- Generate compelling recommendations for potential investment in further work
- Generate significant IP for CAM Testbed UK

The details of Stream 2 and its outcomes are reflected in the second section of this report, authored by Reed Mobility (Nick Reed).

3 | Interoperable simulation

3.1 The role of modelling and simulation (M&S)

Advancements in connected and automated vehicle (CAV) technologies introduced a new disruptive set of products, applications, and services, collectively known as connected and automated mobility (CAM). Development of CAM systems and products require a considerable amount of effort on research and development and billions of miles of testing to cover the complex process of design, development, test and verification (Castignani, 2019). Considering the amount of cost and time involved in setting up real experiments, especially for complex AD systems and massive numbers of test scenarios, it is almost impossible to cover the whole test and development process of CAM products with only real-world testing, and so modelling and simulation (M&S) becomes an essential part of all research, development, test, and validation of CAM technologies and products (Feng *et al.*, 2019).

This project uses the following definition for M&S in this report (Banks *et al.*, 2010):

- A **model** is a physical, mathematical, or otherwise logical representation of a system, entity, phenomenon, or process.
- **Simulation** is the imitation of the operation of a real-world system or process over time.
- **M&S** is a term in itself and not the sum of the two words. M&S is a discipline that comprises the development and/or use of models and simulation(s) (systems).
- A **Synthetic Environment (SE)** is a representation of the real world, within which any combination of players may interact.

It is worth noting the importance of M&S as a common and well-established development approach in the automotive industry (and other industries, including defence and aerospace) within the context of Model-Based Development (MBD) processes (Aarenstrup, 2015). Model-Based Design is a model-centric approach to the development of advanced systems such as control, planning, signal processing, communications, and other dynamic systems. Rather than relying on physical prototypes and textual specifications, a "model" of the system (and its sub-systems), with various level of complexity and fidelity is being used through the entire development process (referred to as the V-cycle) (Socci, 2015).

There are a wide range of advanced (all-inclusive) modelling and simulation software, tools, and solutions available in the market, ranging from free, open-source software and packages to commercial-off-the-shelf (COTS) products from various global vendors. These modelling and simulation packages are being used extensively by a wide range of (academic and industrial) users for simulation tasks and applications at different stages of the development process. These available simulation packages are mostly focused on one or a few domains (such as vehicle, sensor, road, terrain, traffic etc.) but have strong limitations on interoperability, flexibility, and scalability. There are also some comprehensive all-inclusive simulation packages available in the market (both open-source and COTS), with the aim of covering the whole M&S domain (to some extent), but they normally use simple and low fidelity modelling approaches, which are useful for research purposes and/or early stages of the development process, and prototyping.

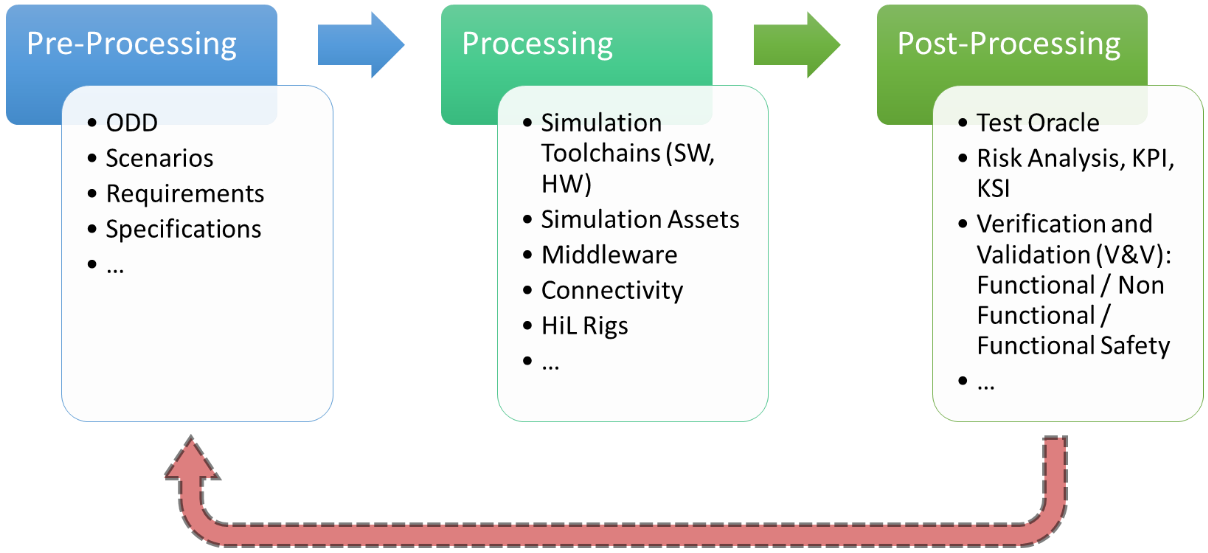
By increasing the complexity and the number of functionalities within CAM systems and products, and also the requirements of running hundreds of thousands of scenario variations, it becomes apparent that none of the existing single simulation tools are capable of running millions or billions of large scale complex simulations runs with adequate levels of comprehensiveness and flexibility. This limitation becomes more critical for real-time applications and for the requirement of having different levels of M&S fidelity to cover the whole Verification and Validation (V&V) process for production level systems and products.

Interoperable simulation seems a promising alternative solution to address some of the current M&S challenges, as briefly highlighted before. Although the topic of simulation interoperability is a relatively new concept in the automotive industry, and more specifically in CAM domains; the benefits and advantages of simulation interoperability, especially for large scale M&S tasks, has been acknowledged in other industries (such as aerospace and defence) for many years (Van Den Berg, Hannay and Siegel, 2016).

Simulation interoperability could be considered as a different approach to M&S in comparison to traditional all-inclusive simulation approaches. Simulation interoperability refers to the capabilities of exchanging simulation models and/or simulation tasks, or simulation in a distributed environment. This is in contrast with traditional centralised approaches which aim to utilise a comprehensive all-inclusive simulation tool, to cover all aspects of the M&S within a single product (such as CARLA, IPG, SCANeR, etc.).

It should also be noted that a complete M&S toolchain for development, test, and validation of CAM systems and products should be considered as an end-to-end solution, consisting of three main steps - :(i) pre-processing, (ii) processing and (iii) post-processing, as depicted in Figure 3.1.

Figure 3.1: An end-to-end CAM simulation process



Source: Author generated

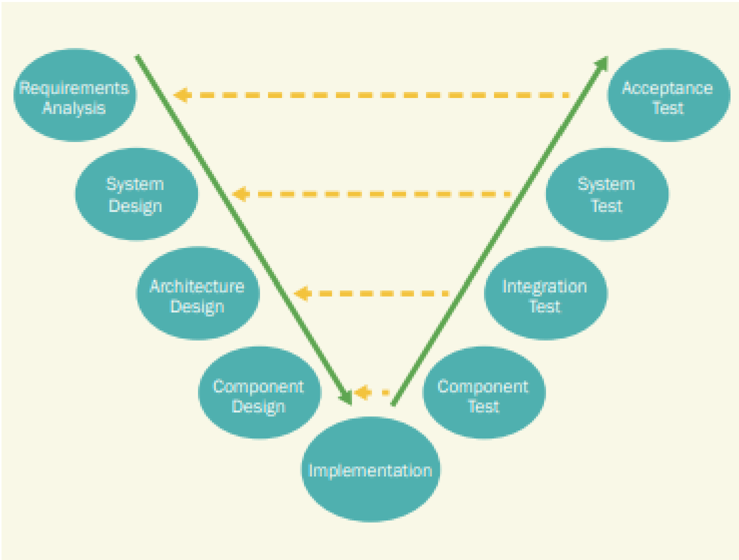
Pre-processing: consists of all the preliminary works that are required to set the simulation toolchains, parameters, and models properly. This may include the definition of the Operational Design Domains (ODDs), scenario descriptions using formats such as SDL and OpenSCENARIO (risk-based approach) and requirements and specifications (functional-based approach) for the System Under Test (SUT).

Processing (simulation run): consists of all the relevant simulation tools, models, assets, algorithms, interfaces, middleware and the associated hardware and software infrastructure to enable a stable simulation execution and reliable results. The aim of the simulation run is to generate the (sufficiently accurate) results for the SUT according to the defined scenarios and test cases. Simulation assets (including the models, algorithms and codes), are specific to any product, application, function or use case to be developed and/or tested. In recent years, some standards and protocols, such as OpenX and JUAS are under ongoing development or revisions by organisations such as ASAM (ASAM, 2021), and SAE (SAE, 2019) to reduce the development and implementation barriers of simulation interoperability.

Post-Processing (test oracle): Post-processing includes the analysis of the simulation results with the aim of discovering critical and edge cases (risk-based approach) or to ensure that the developed system meets the requirements, specifications and functionalities as pre-defined in the system requirements and specifications (functional approach). It is also important to maintain the capability of reproducing the simulation results. This is especially critical if one is to trust the results as part of a certification process.

This CAM simulation process could be executed either as an open-loop or closed-loop. Open-loop simulation setup means that there is no explicit definition and systematic relation (as the feedback loop) existing between the input (Pre-processing) and output (Post-processing) of the simulation in the development process. In a closed-loop simulation setup, on the other hand, the output of the simulation results (Post-processing) will be fed into the simulation input (Pre-processing), to be used for re-adjusting (tuning) or re-defining the initially defined scenarios or specifications, based on the simulation results. The traditional V-model development cycle, as shown in Figure 3.2, (functional based development) is essentially a closed-loop development process (through several feedback loops, including Model-in-the-Loop (MiL), Software-in-the-Loop (SiL), Hardware-in-the-Loop (HiL), or in a general term X-in-the-Loop (XiL). While there is no clear and common agreement about the definition and setup of a closed-loop simulation setup using the risk-based approach, it is a subject of current research among the CAM research community (PEGASUS Project, 2018).

Figure 3.2: The V-Model



Source: Aarenstrup (2015)

3.2 System interoperability

The concept of M&S interoperability can be explained and defined within the context of system engineering. According to INCOSE (INCOSE, 2016):

"A system is an arrangement of parts or elements that together exhibit behaviour or meaning that the individual constituents do not".

The general definition and types of "system interoperability" are provided in this section, and more specifically, they will be used for the definition and explanation of the simulation interoperability in Section 3.3.

System interoperability is defined as the ability of different systems, devices, applications, or products to connect and communicate in a coordinated way, without effort from the end user (Slater, 2012). This concept is being used widely in IT domains to define the functions of interoperable components (hardware and/or software). Different types of system interoperability can be classified as (Serrano *et al.*, 2017):

- **Syntactic interoperability**: Systems that can communicate successfully through compatible formats and protocols. This is also sometimes referred to as structural interoperability.
- **Semantic interoperability**: This is the ability of systems to exchange and accurately interpret information automatically. Semantic interoperability is achieved when the structure and codification of data is uniform among all systems involved.
- **Cross-domain or cross-organisation interoperability**: This refers to the standardisation of practices, policies, foundations, and requirements of disparate systems. Rather than relating to the mechanisms behind data exchange, this type only focuses on the non-technical aspects of an interoperable organisation.

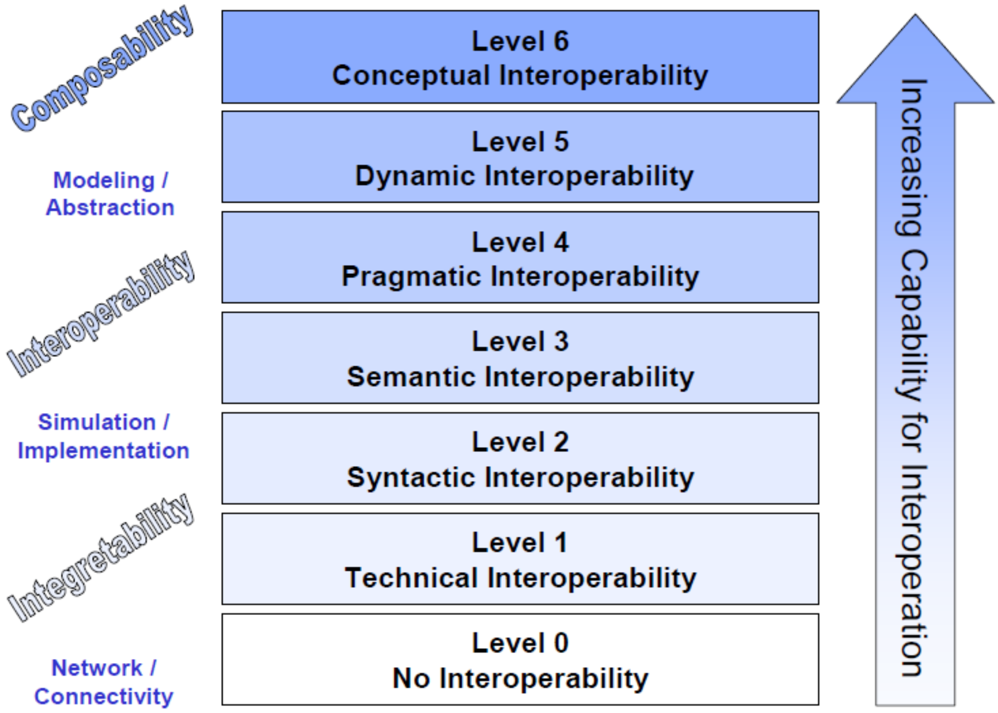
3.3 Simulation interoperability

The definition of system interoperability, as presented in the previous section, is well suited for general system engineering cases and more specifically for IT systems (and also IoT systems), as the only way to make these systems interoperable is to make them interconnected. More specifically for an IT (and IoT) system, interoperability means the ability to exchange data via common protocols in a shared infrastructure.

For simulation systems, however, the exchange and use of data is necessary, but not sufficient. Simulation systems execute models, and, therefore, simulation interoperability requires the alignment of the physical systems represented in the underlying models.

A detailed classification of simulation interoperability has been proposed by (Wang, Tolk and Wang, 2009) presented as the Levels of Conceptual Interoperability Model (LCIM). This model identified and characterised six levels of interoperability and the associated layers for modelling/abstraction, simulation/implementation, and network/connectivity, as shown in Figure 3.3.

Figure 3.1: The levels of conceptual interoperability model



Source: Wang, Tolk and Wang (2009)

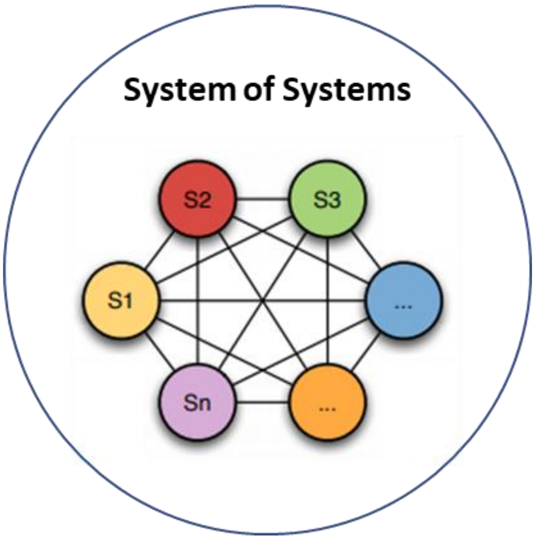
A more simplified version of LCIM, for the definition of interoperable simulation proposed by (Rocha *et al.*, 2010), is as such:

- **Integrability:** The physical/technical realms of connections between systems, which include hardware and its related operating system, firmware, etc.
- **Interoperability:** The software and implementation details of interoperations, including the common protocols and standards for exchange of data elements.
- **Composability:** The underlying models as a valid representation of the real world and the associated dynamic systems, being virtualised by the resulting simulation systems.

Interoperable simulation as a System of Systems (SoS)

The definition of simulation interoperability can be elaborated further using the concept of System of Systems (SoS). By definition, a SoS is a collection of systems (as schematically shown in Figure 3.4) that were originally designed as stand-alone systems for specific and different purposes but that have been brought together within a SoS umbrella to create a new capability needed for a particular mission. A good SoS design might have modules that are not as good as their stand-alone counterparts that perform the same functions. As such, these modules might not be employed independently even though technically they could. A SoS is commonly characterised using terms such as interoperable, synergistic, distributed, adaptable, trans-domain, reconfigurable, and heterogeneous (Madni and Sievers, 2014) (Manthorpe, 1996).

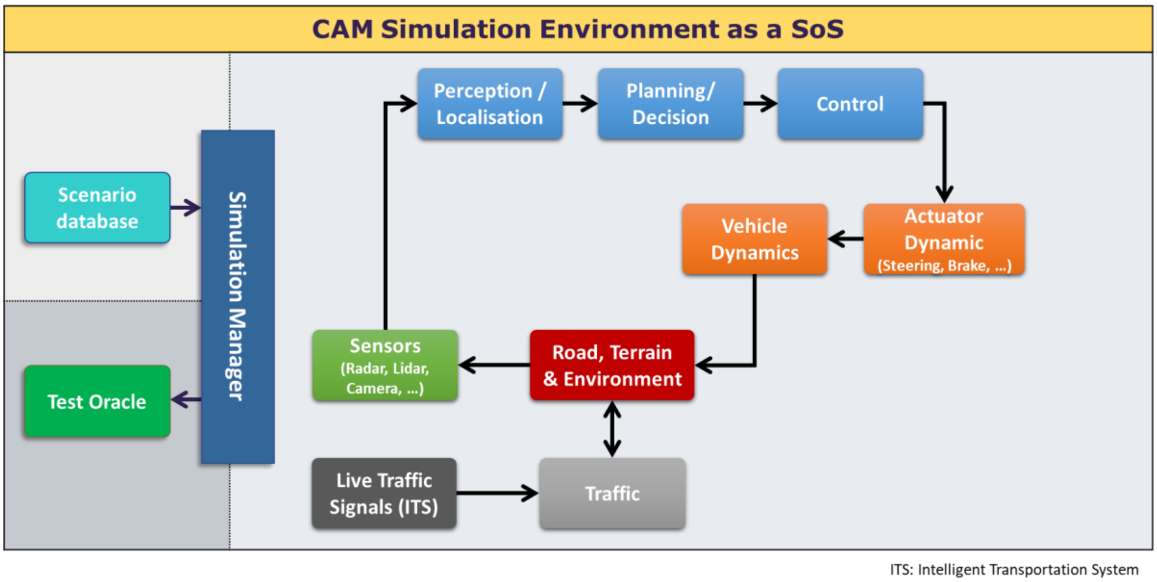
Figure 3.4: A System of Systems (SoS)



Source: Corsaro (2014)

In this approach, the whole CAM simulation environment can be considered as a System of Systems (SoS), and the simulation architecture can consist of sub-systems representing various elements of a CAM system, such as a driver, vehicle, sensors, actuators, road, environment, traffic, connectivity, and the associated underlying AD algorithms such as perception, planning, decision and control, as shown in Figure 3.5, as an example.

Figure 3.5: An Example of CAM Simulation Environment as a System of Systems



Source: Author generated

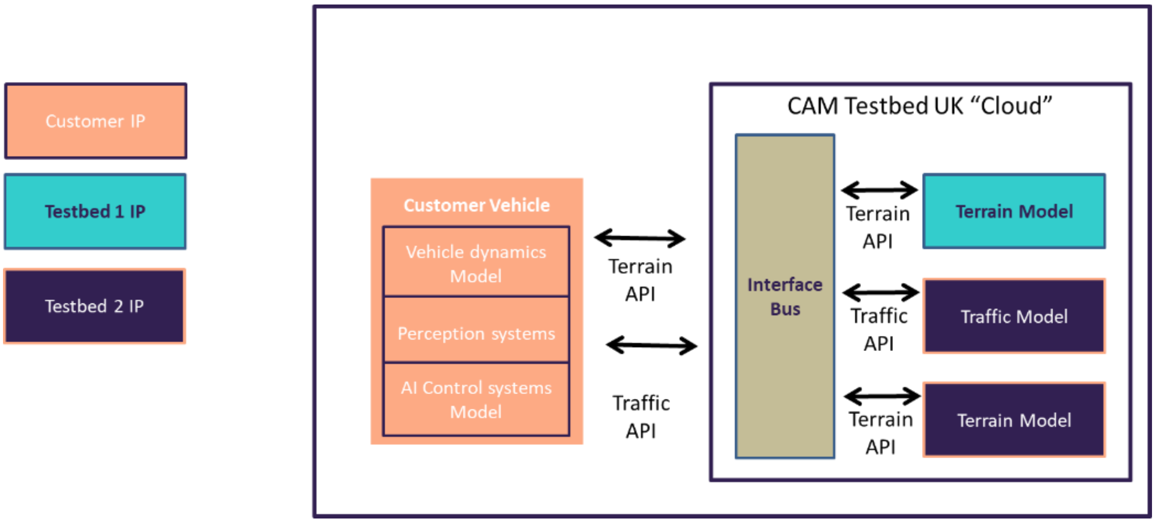
Simulation interoperability options

Representation of an interoperable M&S environment as a SoS, exhibits a wide range of possible options for the system arrangements and its configurations. More specific to this project, simulation interoperability is referred to as the capabilities of exchanging the simulation models, exchanging simulation tasks, or to run a simulation task in a distributed way. The following three options for simulation interoperability, as defined by Zenzic, were accepted and adopted for the design and build of the interoperable simulation PoC in this project:

- **Interoperable models**

Models across sites are in an interoperable format which allows a customer to move between sites easily as shown in Figure 3.6

Figure 3.2: Example of an interoperable model

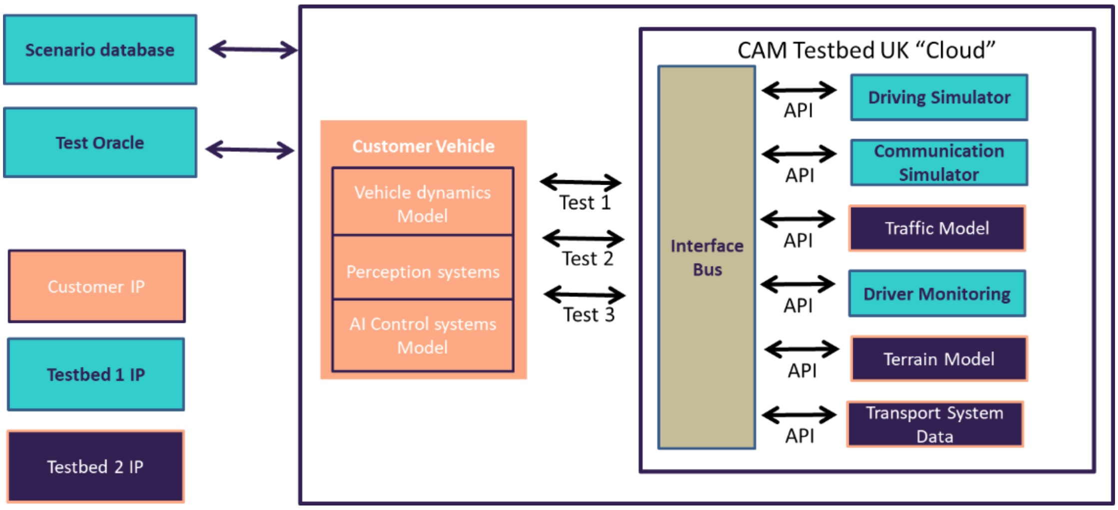


Source: Zenzic

- **Interoperable simulation**

Simulation capabilities across sites are in an interoperable format which allows a customer to move between sites easily to carry out similar tests in different environments or easily draw down capabilities for different tests as illustrated by Figure 3.7.

Figure 3.7: Example of an interoperable simulation

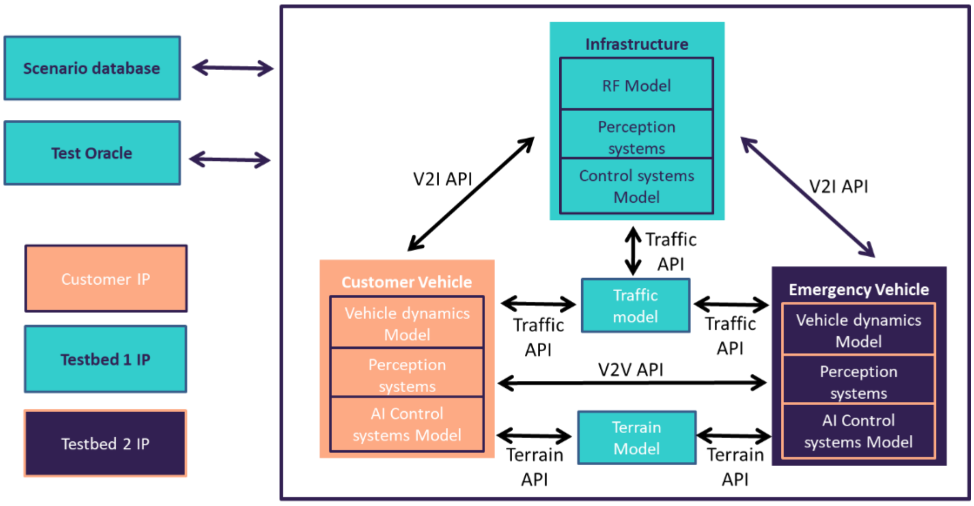


Source: Zenzic

- **Distributed simulation**

Online access to multiple capabilities across testbeds to allow a single test to be performed using the best-in-class capabilities from each testbed as shown in Figure 3.8.

Figure 3.8: Example of a distributed Simulation



Source: Zenzic

3.4 Connectivity solutions for interoperable simulation

According to ISO/IEC 15288:2015 (ISO, 2015)

"A system is a combination of interacting elements organised to achieve one or more stated purposes."

This can lead to the conclusion that connectivity is an essential and integral part of any system. In other words, a system cannot form (and work) without having connectivity in between its sub-systems.

Within the context of a SoS, connectivity is considered one of the fundamental building blocks of any interoperable simulation environment. This connectivity, in its simplest form, could be the capability of exchanging data, models or executable files offline (so named, compatibility), but to enable more complex simulations for example, a real-time distributed simulation, reliable, high bandwidth, low latency connectivity is essential. In other words, the capability of exchanging data between the simulation systems is the minimum requirement, but it is not sufficient to explore the full capabilities and benefits of simulation interoperability.

In a distributed simulation, when all the entitles involved are in one geolocation, high-speed ethernet can be sufficient for the needs of the physical layer. But when simulation entities from multiple geolocations must be connected to serve a use case, one must consider site-to-site connectivity options. Internet can be the first choice when multiple sites must be connected.

As a result of rapid advancements in wired and wireless communication technologies, a wide range of possible connectivity options and solutions are available in the market. These range from simple (and cheap) internet-based connections such as VPNs, to more complex (and expensive) proprietary solutions such as SD-WAN, VPN-over-Internet, MPLS VPN (Multiprotocol Label Switching) and Virtual Private LAN Service (VPLS) (*VLPS Options*, 2021).

Security of the network solution used to achieve connectivity between geographically separated systems is critical when simulation is used for the certification of SUTs. Use of isolated networks and employing advanced security measures like encryption, authentication and secure and resilient system architecture is necessary.

For few data points at a low rate, a simple use of VPN over Internet can suffice the requirements to achieve real-time simulation, but when scaled up, the disadvantages of lacking a Quality of Service (QoS), limited Service Level Agreement (SLA - such as guaranteed latency, bandwidth and availability) and jitter can become more significant (Bhardwaj, 2021). On the other hand, for MPLS or similar connectivity solutions, the service-provider provides guaranteed packet prioritization and delivery, including end-to-end delay, defined SLA's (Cato networks, 2017), which can become beneficial to achieve deterministic real-time simulations as things scale up.

As the number and complexity of systems involved in the simulation increases, the bandwidth can become the bottleneck to real-time simulation. Having a high bandwidth connection can enable the ability to have more systems geographically separated. This also enables the ability to run multiple simultaneous simulations involving multiple geographically separated locations.

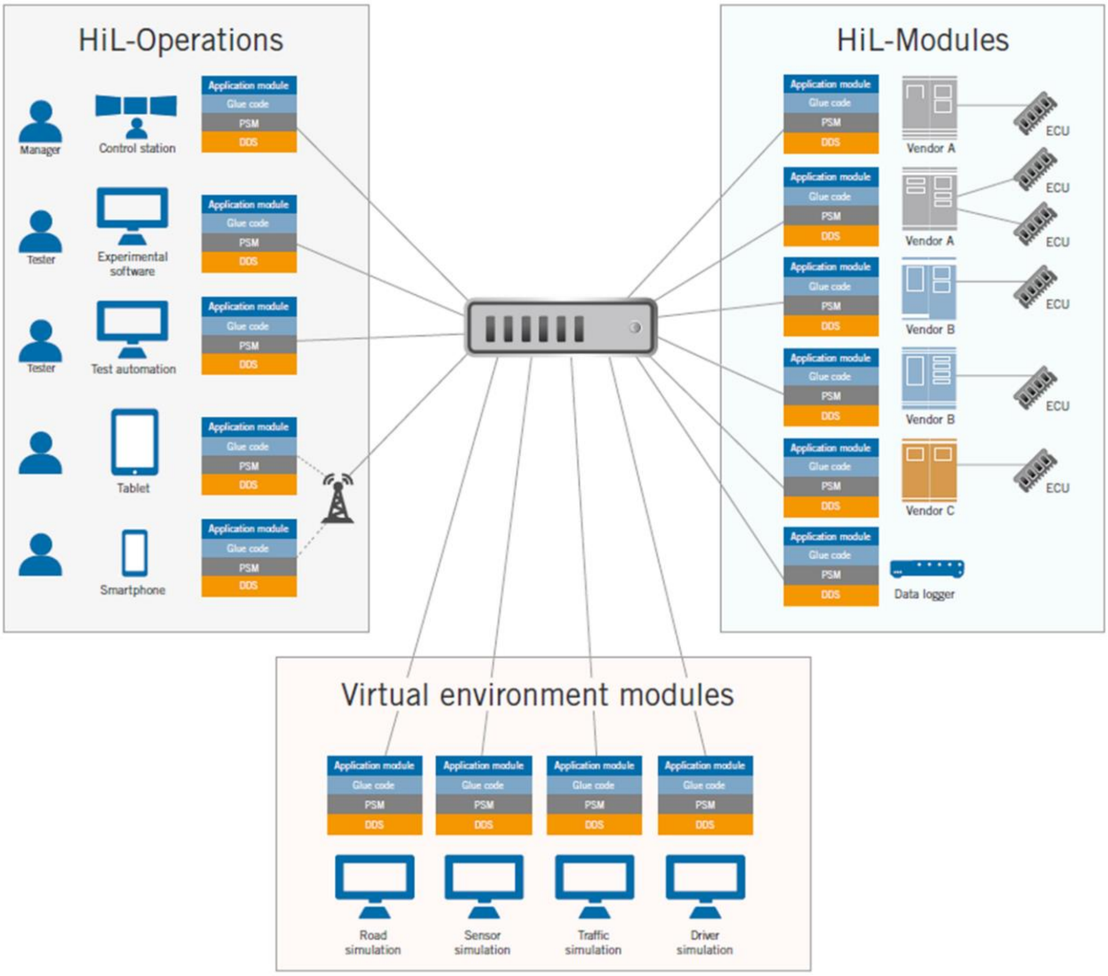
Scaling of connectivity to multiple sites needs to be seamless. The benefits of having access to the cloud are stronger than ever and having the ability to scale the simulation infrastructure to cloud is paramount. Using purely traditional site-to-site connectivity solutions (point-to-point VPLS or VPN-over-Internet) can become cumbersome to setup when the number of geographically separated systems to be connected increases, and unnecessary when connection to a new site is only needed for specific durations.

Using a hybrid approach (MPLS and Internet) can be beneficial by making the connectivity more flexible, agile and cost effective. Cost effective VPN-over-Internet solutions can be used when and where MPLS connectivity is not available or when the latency tolerance is higher. The hybrid approach (like SD-WAN, which allows connectivity over broadband internet, 4G/5G or MPLS) (Paul. Justin, 2021) can prove to be resilient and reduce the downtime due to network connectivity issues by switching to backup connection lines and prioritising the critical data (Yang *et al.*, 2019)(Silver peak, 2021).

3.5 Interoperable simulation architecture

With the advent of CAVs, and the resultant increase of the number of Electronic Control Units (ECUs) in automotive systems, traditional ECU-centric based simulations are incapable of replicating system behaviour to a sufficient degree of accuracy. Automotive systems are becoming truly distributed. Simulating such complex systems brings new challenges to ensure interoperability and reusability between components/systems. Some OEMs are now investigating the use of such distributed simulation architectures which allow for interoperability as illustrated in Figure 3.9 (Brückner and Swynnerton, 2014).

Figure 3.9: Audi's distributed HiL architecture



Source: Brückner and Swynnerton (2014)

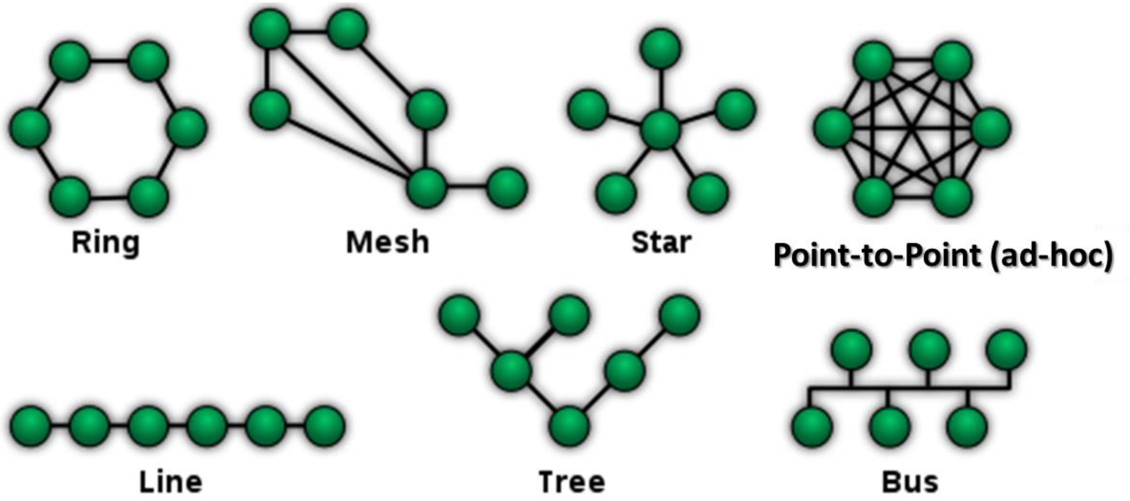
CAVs incorporate a multitude of highly specialised systems for operation, such as sensing, perception, localisation, planning, control and communication. Currently available simulation solutions are not designed to fulfil the complex requirements of modern CAM products, as well as to provide large-scale distributed simulations. Simulating such a complex SoS is not achievable without following a systematic approach.

In this project a systematic data centric approach for building a scalable and efficient interoperable simulation architecture was proposed. A data-centric approach eliminates the need to match compatibility between different vendors, allowing for a highly flexible and scalable testing environment (RTI, 2014).

Point-to-point integration vs data bus integration

Considering an interoperable simulation environment as a System of Systems (SoS), the possible combination of system interconnections could be defined as a network topology. Network topology (or architecture) can be considered as a graphical representation of the physical or logical arrangements of the elements (sub-systems) of a system. Some common types of network topology include ring, mesh, star, line, tree, point-to-point (ad-hoc) or bus topologies, as schematically shown in Figure 3.10.

Figure 3.10: Various network topologies



Source: Author Created[3]

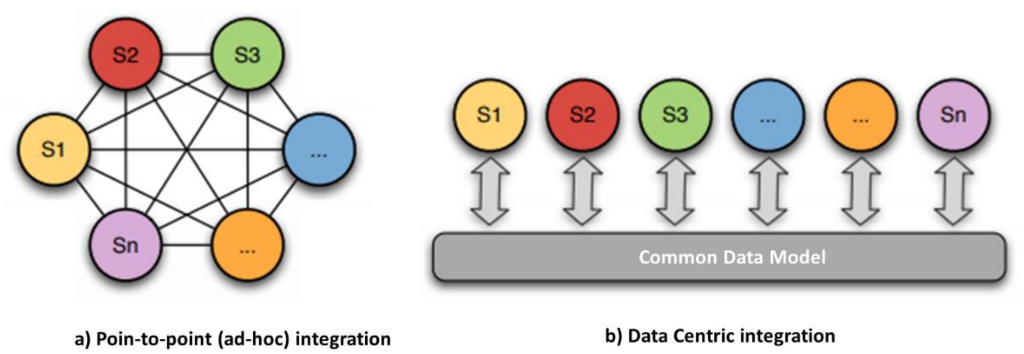
Conventional approaches to integrate simulation software involve some form of point-to-point solutions, using well known methods such as API interfaces, Functional Mock-up Interface (FMI) or Functional Mock-up Units (FMU), which lead to some forms of point-to-point topologies (such as line, ring, star, ad-hoc, etc). While point-to-point solutions are effective for simple integrations with few numbers of sub-systems involved, this approach has several shortcomings, including:

- **Scalability**: by increasing the size of the system and the number of the sub-systems, point-to-point solutions become very complex to design and difficult to implement, as it requires the n-1 integration within the system (for n subsystems).
- **Efficiency**: point-to-point architectures are not resource efficient, as they duplicate the flow of information,
- **Flexibility**: it is difficult to modify the system, as each change usually needs to be propagated on the n – 1 point-to-point integrations.

[3] adopted from https://www.educba.com/types-of-network-topology/

To overcome the structural issues of point-to-point integration, a decentralised data centric approach (bus architecture) seems a better alternative to architect an interoperable simulation environment, as depicted in Figure 3.11. In this approach, a bus architecture is employed for the system and the focus is more on defining a common set of abstractions, called the common data model, rather than on the complexity and challenges of the network topology. This approach reduces the time and effort needed for the development and implementation of an integrated simulation system. It migrates some effort to the careful design of the common data model and reduces (in some cases eliminates) the integration effort, since all systems communicate using the same protocol and type system. The common data model is used to represent all information that is necessary and relevant for the inner workings of the interoperable simulation system (Anthony, 2016).

Figure 3.11: Ad-hoc integration vs Data centric integration



Source: Corsaro (2014)

The essential step toward the design of a data centric architecture is to build a common data model, using languages such as OMG Interface Definition Language (IDL)™, (also available as ISO standard ISO/IEC 19516:2020). It involves defining data types and interfaces in a way that is independent of the programming language or operating system/processor platform (Object Management Group, 2018). The defined data model can then be linked together to form an integrated data centric system, using various middleware solutions.

3.6 Simulation middleware

Middleware includes software which provides links between the operating system and applications, allowing for seamless connection and data-sharing, greatly simplifying the development of distributed systems. The simulation middleware should possess favourable characteristics in terms of ease of integration, scalability, security, and reliability. In addition, for distributed simulation of extremely complex SoSs such as CAVs, several other features such as: configurability, redundancy, flexibility on programming language, operating system, hardware, and data type, are also important.

Middleware solutions

There are many communications middleware standards and products. Some of the more popular IoT-based communication protocols include Message Queue Telemetry Transport (MQTT), Advanced Message Queuing Protocol (AMQP) and Constrained Application Protocol (CoAP) as illustrated in Table 3.1. However, these protocols are unsuitable for use in complex large-scale distributed simulation systems, especially because they can hardly satisfy the strictly required Quality of Service (QoS) expectations for industrial IoT (IIoT) applications. To alleviate the difficulties faced in such applications, Data Distribution Service (DDS) is seen as an ideal choice. DDS is uniquely data centric, which is ideal for distributed simulation. Most middleware works by sending information between applications and systems. Data centricity ensures that all messages include the contextual information an application needs to understand the data it receives.

Table 3.1: Comparison between examples of middleware solutions

	Transport	Paradigm	Scope	Discovery	Content Awareness	Data Centricity	Security	Data Prioritisation	Fault Tolerance
AMQP	TCP/IP	Point-to-Point Message Exchange	D2D D2C C2C	No	None	Encoding	TLS	None	Impl. Specific
CoAP	UDP/IP	Request/ Reply (REST)	D2D	Yes	None	Encoding	DTLS	None	Decentralized
DDS	UDP/IP (unicast + mcast) TCP/IP	Publish/ Subscribe Request/ Reply	D2D D2C C2C	Yes	Content-Based Routing, Queries	Encoding Declaration	TLS, DTLS, DDS Security	Transport Priorities	Decentralized
MQTT	TCP/IP	Publish/ Subscribe	D2C	No	None	Undefined	TLS	None	Broker is the SPoF

TCP: Transmission Control Protocol **IP:** Internet Protocol **D2D:** Device-to-Device **D2C:** Device-to-Cloud **C2C:** Cloud-to-Cloud
TLS: Transport Layer Security **DTLS:** Datagram Transport Layer Security

Qualitative Comparison of IoT Standards

Source: DDS Foundation (2019)

The DDS is a middleware protocol and API standard for data-centric connectivity from the Object Management Group® (Object Management Group, 2021). It integrates a system's components, providing low-latency data connectivity, extreme reliability, and scalable architecture that business and mission-critical IIoT applications need.

DDS knows what data it holds and how to distribute it, which is the nature of data centricity. The global data space, as defined by DDS, is a local store of data. The global storage space appears to the application as local memory that can be accessed through an API. You make a write to what appears to be local storage. DDS sends messages to remote nodes to update the necessary stores.

DDS middleware can be configured to handle edge-to-edge QoS policies. However, the unpredictability of the environment makes the development and implementation of these systems more complex. The publish/subscribe middleware has enhanced the distributed systems' scalability and interoperability. The stricter QoS specifications are, the more difficult it is for developers.

DDS's scalability and various transport configurations make it ideal for real-time embedded systems. DDS fulfils the protection, resilience, scalability, fault-tolerance, and security criteria of distributed systems. DDS can provide solutions for real-time environments and small/embedded systems by reducing library sizes and memory footprints. Developed by different DDS vendors, several implementations of this communication system have been used in mission critical environments (e.g. trains, aircrafts, ships, dams, and financial systems) and have been verified by NASA and the United States Department of Defence. Researchers and DDS vendors have tested and validated many DDS implementations. DDS is both reliable and flexible, according to these.

ROS2, the successor of ROS (Robot Operating System), the most widely used open-source software framework for robotic research and development, is based on DDS due to its safety certification and performance reliability (Thomas, 2017). In addition, the AUTOSAR Adaptive platform which is the standardised automotive open system architecture designed for automotive Electronic Control Units (ECUs) with high performance compute and connectivity requirements, can work together with DDS to enable interoperability and advanced functionality (Richte and Cameros, 2021)(Parmar, Ranga and Simhachalam Naidu, 2020). Both ROS2 and AUTOSAR are prime examples of how important the high performance, scalable and data centric characteristics of DDS are in the development of CAM. The same qualities also make DDS the ideal candidate for the middleware framework of distributed and interoperable simulation for CAM SoSs.

4 | Zenzic interoperable simulation proof of concept

4.1 Project deliverables

The interoperable simulation PoC was defined as a continuation of the previous project (Zenzic Interoperability Project, Phase1) and aims to set the foundation and plan for a potential next phase (Zenzic Interoperability Project, Phase 3). A brief description of the project, its aims and objectives, and phases, have been provided in Section 2.

The project partners are three CAM Testbed UK partners: Millbrook Proving Ground (Millbrook-Culham Urban Testbed), Smart Mobility Living Lab: London (SMLL) and WMG (Midlands Future Mobility), aiming to provide a solution to the customer (StreetDrone) with in-kind contributions and support received from various global companies, including: IPG, PVT, RTI, and Nissan.

Millbrook owned the overarching technical delivery of the demonstrator, to:

- define the technical architecture and interface design of the demonstrator
- take responsibility for testing and validation
- delivery of the integration platform of the demonstrator
- create an open simulation framework which will scale for future operational deployment across CAM Testbed UK
- support the development of recommendations, with Zenzic, to build the commercial and operational case for potential further work
- work with the testbed partners to define the most effective demonstrator
- work with Zenzic to engage potential users and work with them to ensure an effective partnership.

4.2 Benefits and added value

A range of simulation tools and assets are being developed at each of the CAM Testbed UK facilities. These have been used in models and simulation applications by each of the testbeds. However, prior to this project, there has been little interoperability between them and, where the data or the application is proprietary, this makes it more difficult to implement interoperability. This project aims to provide a demonstration of how CAM Testbed UK can link diverse systems to create interoperable distributed simulations.

In addition to a range of new innovations that have been generated as part of the project delivery, the partners worked together in a collaborative manner, exchanging background and foreground IPs, which brought challenges throughout the duration of the project.

Simulation is a cornerstone for delivery of scalable CAM services nationally and internationally. It is vital for safety and a key component for service delivery. However, simulations in this sector are siloed and are often not validated across different systems. This project provides early learning on governance and technical integration standards that sets foundations for approaches in CAV PASS (Gov.uk, 2019) and wider global standards putting the UK in an excellent leadership position.

This project has also delivered a PoC of a globally-significant capability and provided learning about broader technical integration and the customer journey across CAM Testbed UK. The initial capability sets clear direction for development of a long-term solution, and in doing so has rapidly identified and solved many technical challenges, while setting the foundations for more significant collaboration long term.

Above all, this first harmonised technology project across CAM Testbed UK delivers substantial value to both government and industry. In addition to the technical value, the marketing output amplifies a key message on world-class capabilities which can be capitalised on to attract new leads to the testbeds.

Importantly, this project solves the challenge of an automated driving system (ADS) developer being able to thoroughly assess the capabilities of their system. In order to provide a robust and comprehensive sense of system performance against the system requirements, a developer must expose their system to a breadth of simulation capabilities.

As discussed in Section 3.1, no single simulation tool is capable of running the millions or billions of large scale complex simulation runs with adequate levels of comprehensiveness and flexibility. However, this project's interoperable platform, both affords access to a variety of geographically disparate simulation capabilities, whilst also providing a seamless, flexible and cost-effective way to interact with these capabilities.

4.3 The project customer, use-case and scenarios

The main purpose of the project is to provide added value to the customer, by offering new simulation features and/or capabilities that cannot be covered by one single testbed's capabilities. Having a customer on board was one of the project deliverables, to ensure that:

- the simulation facilities are capable to integrate with the existing AD functions that have been developed by the customer
- the simulation service is fit for purpose and acceptable by the customer.

Several potential customers were identified in the initial selection process; Zenzic selected StreetDrone as the project customer.

Innovative start-up StreetDrone play an active role within the CAM ecosystem as a vehicle and AI stack provider to three CAM Testbed UK testbeds (in 4 locations, including RACE), as a participant in CCAV funded R&D consortia, and as a supplier to the wider UK CAM Ecosystem players (Ordnance Survey, Parkopedia, Coventry University).

They are developers of unique vehicles, and industry leading open-source software and hardware interfaces for the wider CAM community. They are UK owned and based, yet with an increasing international reach, including research institutions and industry. With a varied vehicle range with fully working AI stacks, based on Autoware and ASLAN, they are ideally suited, in terms of their development philosophy and suitability, across many use cases and CAM Testbed UK capabilities. Being open-source and part of a community, are among the benefits of working with StreetDrone, as this ensures a wider applicability to the interoperable simulation, and not a single customer-centric approach.

The main justifications for selecting StreetDrone as the project customer were:

- **Interest and commitment:** StreetDrone showed great interest to get involved in this project and committed in-kind and support to the project.
- **Agility**: Considering the short project duration and the required agility in this project, StreetDrone as a UK based SME, could provide quick and efficient first-hand access to the technical support and resources that were required for this project.
- **Availability of vehicle platform**: StreetDrone has developed a number of automated vehicles based on various vehicle platforms, including Renault Twizy and Nissan eNV200, which have been utilised by CAM Testbed UK before, and the vehicle platform and its technical specifications are known to CAM Testbed UK.
- **Availability of AD software platform**: StreetDrone has also developed an open-source full stack AD software, Project ASLAN, which is a modified version of Autoware (ROS1) and it includes all the basic AD functions, including perception, planning, localisation, decision and control.

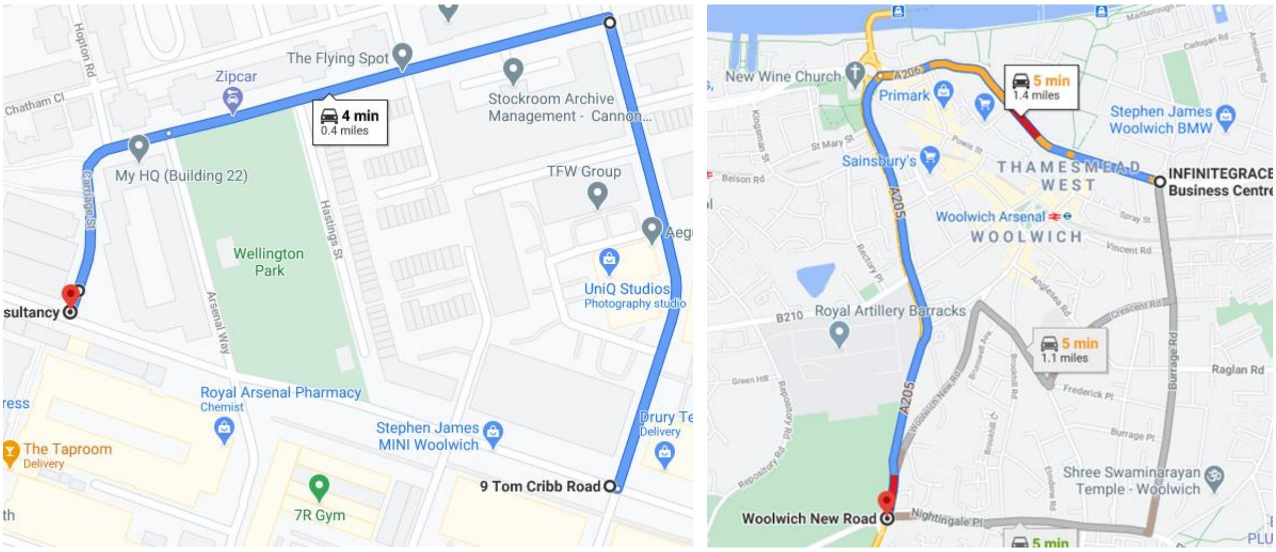
The route to engagement was to use a virtual model of the vehicle and its software stack (ASLAN) within the simulation, tailored to the specific use case that was developed as the PoC. As the majority of the access to the AD software stack is open source, there were less IP complications for the PoC integration.

For the purpose of this project, the Nissan eNV200 vehicle was selected from the available automated vehicle platforms from StreetDrone, to be modelled in the simulation environment, as the ego vehicle. SMLL already has two vehicles in operation, one of which was deployed at the WMG 3xD simulator for the purpose of project demonstration. Millbrook also utilised one of its Renault Twizy StreetDrone vehicles for ASLAN implementation, and demonstration at the Millbrook Vehicle Simulator.

The goal of this simulation PoC was defined as: the integration of several of ASLAN's inbuilt self-driving algorithms, including localisation, path planning, object detection, decision, and control, with a distributed interoperable simulation platform, and assessment of their functionalities along various routes around the SMLL main office in Woolwich, London.

Two sections of route around the SMLL main office, as shown in Figure 4.1, were selected to perform the simulation run, namely route A and route B.

Figure 4.1: SMLL Route A and Route B



Route A

Route B

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The reasons for selection of these routes were:

- the initial models of both routes had been previously developed by SMLL (in 3DS) and were available to share with Millbrook for the purpose of this project
- StreetDrone had already tested some of ASLAN's functions with a real vehicle along route A, so the results of real-world testing for some of the ASLAN functions (localisation) were available
- SMLL had already integrated real traffic signals (via SCOOT) into the traffic simulation (via Vissim), for route B.

Two different simulation setups were considered to demonstrate various interoperability options in this PoC project:

- **Demonstration 1**: Test of ASLAN functions against several predefined scenarios along route A, using various options of interoperable simulation.
- **Demonstration 2**: A distributed simulation setup with a random traffic model, integrated with live traffic light data across route B. (also simulated across route A, but without SCOOT integration, as there are no traffic lights along this route).

For the purpose of the first demonstration, five different scenarios were defined along route A as below:

- Scenario 1 (A1): Pedestrian crossing at Armstrong Road.
- Scenario 2 (A2): Traffic vehicle right turn with cut in
- Scenario 3 (A3): Pedestrian crossing at Cadogan Road
- Scenario 4 (A4): Pedestrian crossing at Carriage Street
- Scenario 5 (A5): Large vehicle obstructing field-of-view while pedestrian crossing at Carriage Street

The details of the scenarios were defined using a scenario description language (SDL), developed by WMG (Zhang, Khastgir and Jennings, 2020)(Khastgir and Mimeche, 2019). More details of the project scenarios and the corresponding SDL scripts are provided in Appendix B.

As part of the simulation interoperability demonstration, the developed SDL files for the defined scenarios were uploaded to WMG's National Scenario Database (NSDB)(Midlands Future Mobility, 2020). Remote access to the scenario files, through APIs, was provided by WMG that was integrated into the simulation environment at Millbrook.

4.4 Simulation models

A wide range of models for the vehicle, environment, sensor and traffic were developed or utilised for the purpose of this PoC project. Additionally, capabilities of "model interoperability" among the testbed partners were examined and demonstrated. This included co-development of the environment model, and exchanging the developed vehicle, sensor and traffic models between testbed partners.

(Ego) vehicle model

With support of Nissan and IPG, a detailed and high-fidelity vehicle dynamics and actuator dynamics model of the ego vehicle (Nissan eNV200) was developed in CarMaker. This vehicle model was used in Millbrook's simulation setup.

Alternatively, the vehicle dynamics model for the same vehicle but, with lower fidelity, was developed in rFpro (internal vehicle model), and was used for the ego vehicle model in WMG's simulation setup.

Environment model

rFpro was used for modelling the environment, including road, terrain, street furniture, and also the visualisation of the ego vehicle, and static and dynamic traffic objects. Based on a joint effort between SMLL and Millbrook, a detailed and photorealistic model of the SMLL route A and route B was developed. In this collaboration, the original model (developed in Autodesk 3ds Max and based on laser scanned data from the SMLL routes) and some of the building textures were provided by SMLL, and complete environment model for the routes was developed in rFpro by the Millbrook team.

Similarly, the shell model (in rFpro) of the ego vehicle (StreetDrone eNV200 vehicle) was also developed by the Millbrook team, based on the original (Autodesk 3ds Max) model of the vehicle provided by SMLL.

Sensor model

The StreetDrone eNV200 vehicle is equipped with various sensors, including Lidar from Velodyne (Velodyne Lidar, 2021), for the generation of point cloud and ground truth data, to be used for localisation and path planning. A physics-based model of a real Lidar sensor, integrated with rFpro environment, had already been developed by Claytex (Claytex, 2021a). This model was utilised in both the Millbrook and WMG simulation setups for the purpose of this project.

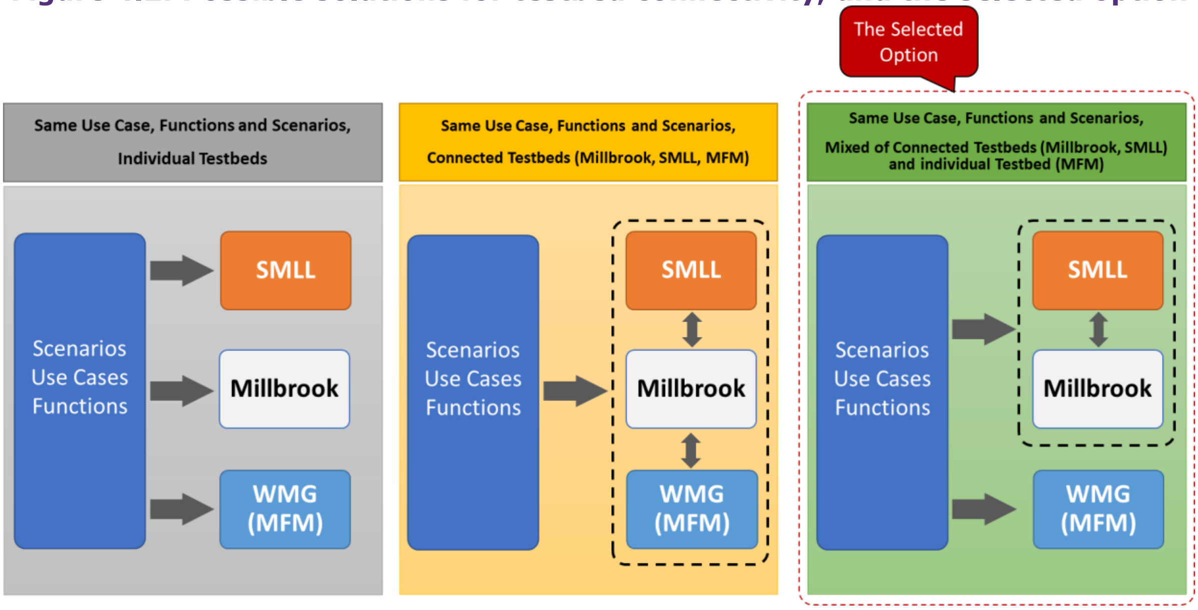
Traffic model

A complete traffic model for both SMLL routes was developed in Vissim and SUMO microscopic traffic simulation software, based on the joint efforts between Millbrook and SMLL. The data of the route geometries was taken from the original models of the route developed by SMLL in Autodesk 3ds Max and was converted to OpenDRIVE format, to be used in VISSIM. The same data was used to create the traffic route model in SUMO, to be used by WMG.

4.5 Connectivity infrastructure

Connectivity is considered as one of the key enablers for simulation interoperability, as briefly discussed before. To utilise the full benefits of simulation interoperability by having a distributed simulation environment, the necessity of reliable and high-quality connectivity becomes more critical. The initial plan for the purpose of this PoC project, was to establish a high bandwidth, low latency, dedicated connection between the three testbed partners, using one of the solutions presented in Section 3.4. However, during the course of the project, the plan evolved as a result of technical and organisational limitations. One of the main technical challenges was the long lead time required by the IT providers, to establish dedicated internet lines, which was beyond the timeline of this project. The resulting solution for the PoC can be seen in Figure 4.2 with connectivity established between Millbrook and SMLL.

Figure 4.2: Possible solutions for testbed connectivity, and the selected option



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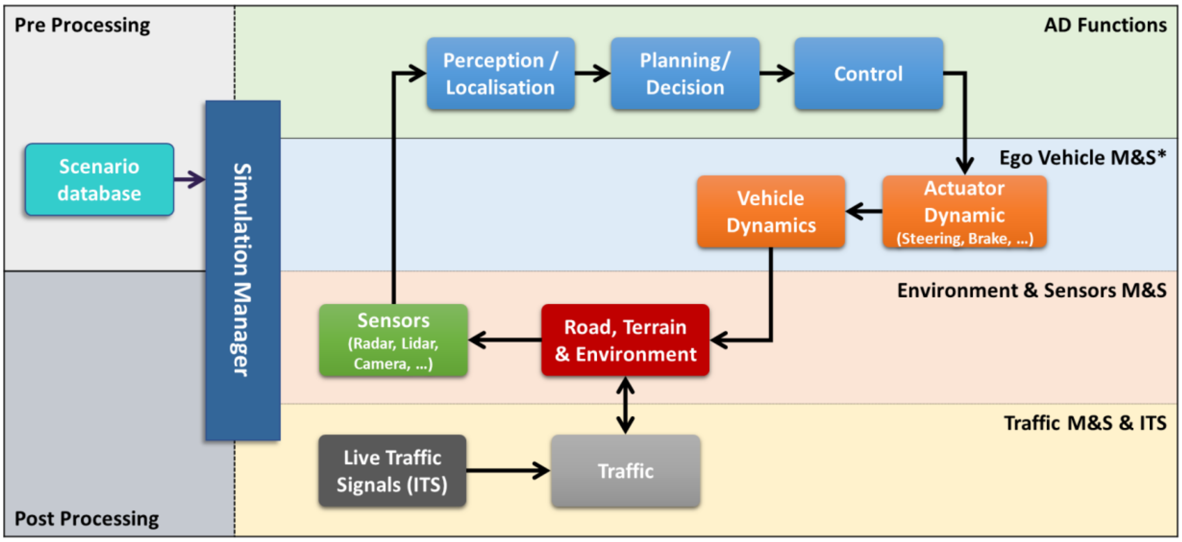
4.6 The simulation architecture

As explained in Section 3.3.1, an interoperable simulation environment could be considered as a System of Systems (SoS) including several interconnected sub-systems, interacting with each other and with the main system. For the purpose of this project, the system integrator proposed the following decomposition of the simulation system:

- ego vehicle: including vehicle dynamics and actuator dynamics.
- environment: including the road, terrain, and furniture, static and dynamic objects, etc
- sensor: including Lidar, Radar, camera etc
- traffic: micro-traffic simulation
- ITS: live traffic signals from the SMLL route
- AD functions: ASLAN software stack for autonomous driving functions, including perception, localisation, path planning, decision, and control
- scenario database, as explained in the previous section.

A schematic diagram of the interoperable simulation system and its architecture is shown in Figure 4.3.

Figure 4.3: Interoperable Simulation Environment as System of Systems



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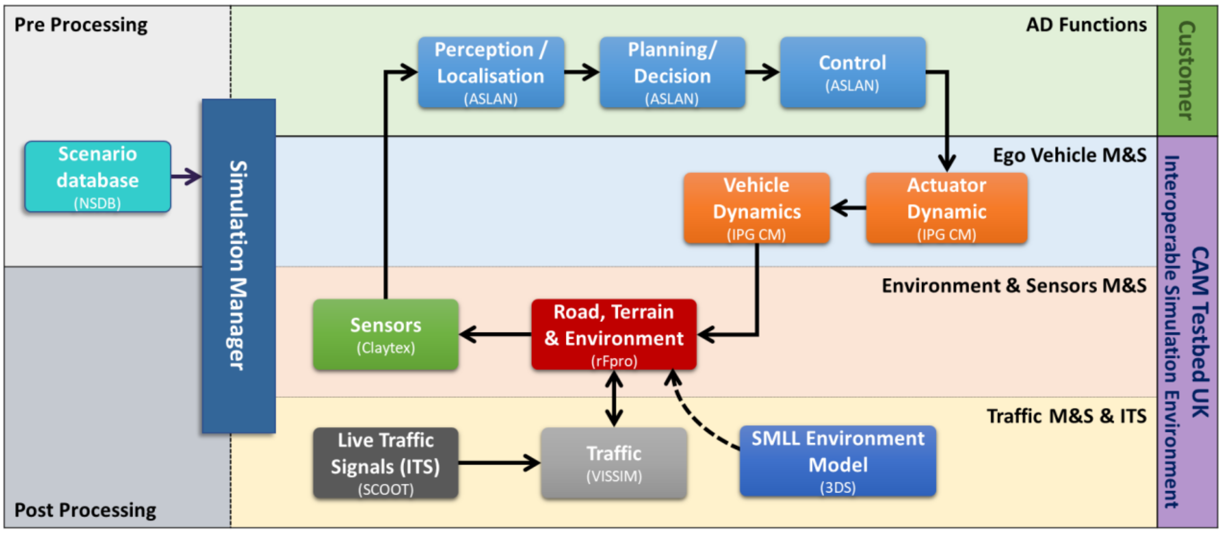
Based on CAM Testbed UK partners' capabilities (as identified in the phase 1 of the project), the following software tools were selected to be integrated with each other to form an interoperable simulation environment, illustrated in Figure 4.4:

- rFpro: for environment modelling including the road, terrain, and environment furniture, and visualisation of dynamic actors (ego and traffic vehicles, pedestrians) M&S
- IPG CarMaker: for vehicle dynamics and actuator dynamics (ego vehicle) M&S
- Claytex: for Lidar and Radar sensors M&S
- Vissim: for microscopic traffic M&S
- SCOOT: for live traffic light data (ITS)
- ASLAN: the customer's full stack of autonomous driving (AD) algorithms and functions.
- WMG's National Scenario Database (NSDB): to host the project scenarios (SDL files)
- An internally developed simulation manager software (KAN Simulation Manager), to setup the simulation parameters and run the scenarios seamlessly.

Figure 4.4: The Interoperable Simulation PoC



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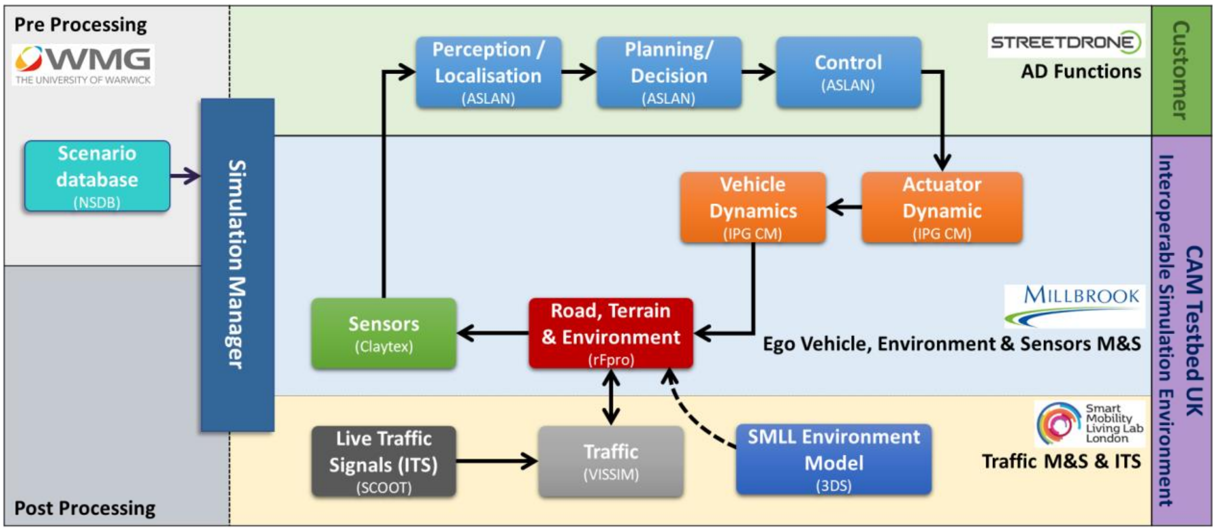
Based on the capabilities identified between Millbrook and SMLL, and the possibility of having connectivity between the two sites, a **distributed simulation** setup for the interoperable simulation PoC was proposed, as shown in Figure 4.5. In this real-time co-simulation configuration, the simulation of the ego vehicle (IPG CarMaker), environment (rFpro) and sensor (Claytex) and its integration with the customer's AD software (ASLAN) was performed at Millbrook, while the traffic simulation (Vissim), integrated with the live traffic signals provided by SCOOT, was running at SMLL. The real-time communication between the two sites, was established with a dedicated internet line (IP tunnelling), as explained in Section 3.4. The aim of this PoC was to demonstrate the capability of **model interoperability** and **distributed simulation** across the two testbeds.

Figure 4.5: Distibuted Simulation setup between Millbrook and SMLL



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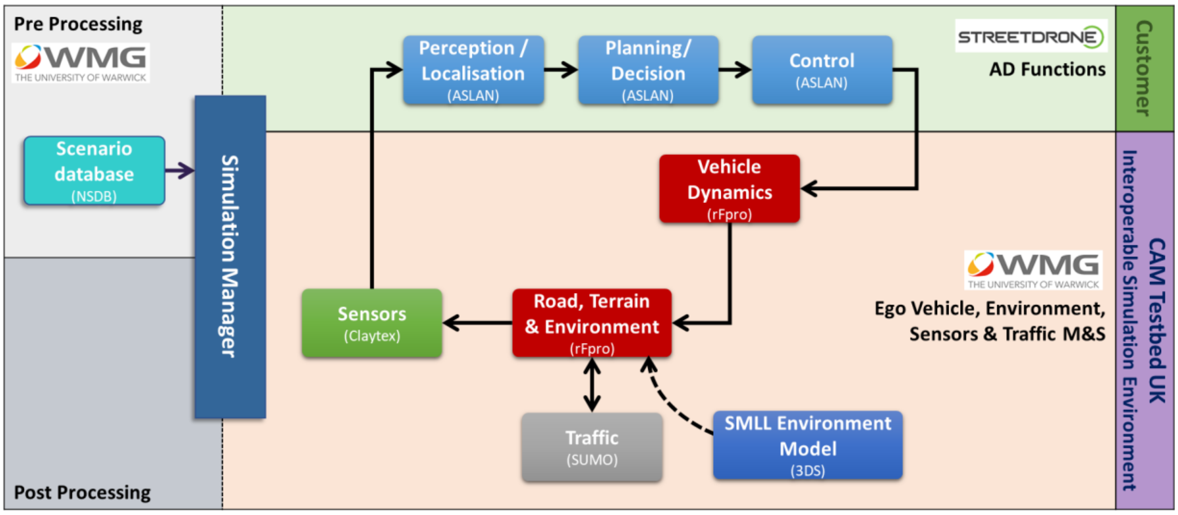
Considering differences between the simulation software and toolchains at WMG and Millbrook, and the fact that no (real-time) connectivity was established between WMG and Millbrook (or WMG and SMLL), a modified simulation architecture was proposed for WMG as a standalone interoperable simulation setup. The aim of this PoC was to demonstrate the capability of **model interoperability** and **simulation interoperability** across the two testbeds, by running the same scenarios, integrated with the same AD software, but with two different simulation setups and toolchains (see Figure 4.5 and Figure 4.6).

Figure 4.6: Interoperable Simulation setup at WMG



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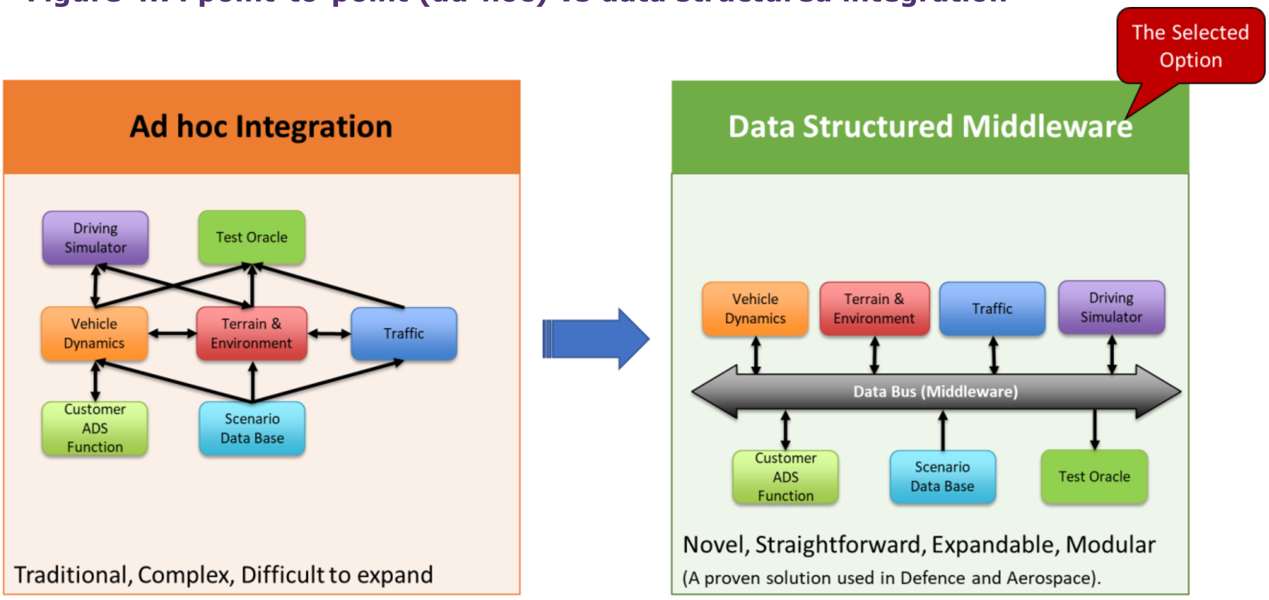
An expandable and interoperable data bus structured simulation architecture based on DDS middleware was proposed for the integration of the simulation software in this project. This architecture could be considered as a foundation for the future development of a real-time distributed simulation environment (XiL) across CAM Testbed UK. The data bus architecture has several advantages, in contrast to traditional point-to-point integration, including modularity and scalability which is crucial for the development of a large scale and complex interoperable simulation environment in the future. Using DDS middleware for the simulation integration, provides several unique features including hard real-time capability, and QoS, as explained in Section 3.6.

Figure 4.7: point-to-point (ad-hoc) vs data structured integration



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More details of the project achievements and results are provided in Section 5.

5 | Zenzic interoperable simulation implementation (PoC build)

A summary of the project outcomes, deliverables and achievements are presented in this section. Thanks to the close and productive collaboration among all the project partners, the customer, and effective help from industrial contributors (IPG Automotive, PTV, RTI and Claytex), the project team managed to generate significant and successful results, within three months. The project saw effective collaboration between the CAM Testbed UK partners, by creating and demonstrating a range of new world-leading M&S capacities, which are beyond the capabilities of any single CAM Testbed UK facility.

A brief description of the project achievements and outcomes are presented in this section.

Project component	Project achievement or outcome
Customer: The main activities and added value to the customer.	Customer onboard
	Definition of the project scenarios, use-case and functions.
	Integration of ASLAN software and its AD functions into the simulation environment, for offline simulation and real-time simulation with Vehicle-in-the-Loop.
	Integration of the Nissan eNV200 vehicle into the vehicle simulators (WMG’s 3xD and Millbrook vehicle simulator).
	Ran a range of scenarios to challenge the ASLAN AD functions, using high fidelity models and advanced simulation tools, and providing the simulation results.
Testbed partners: The general achievements and added value to the testbed partners.	Demonstrated a successful example of a joint effort and productive teamwork, by bringing together each testbed’s unique expertise, capabilities, and the exchange of background IPs.
	Created a range of new world-class interoperable simulation capabilities beyond the capacity of any single CAM Testbed UK facility.
	Implementation of an (initial) framework for clarification, protection, registry, rights, and ownership of the project (background and foreground) IPs.
Simulation Infrastructure:	Studied and suggested options for the connectivity (between the testbed partners)

Implementation of the solutions for the simulation connectivity infrastructure, including:	Implementation of the agreed connectivity solution between Millbrook and SMLL (IP tunnelling)
	Implementation of the remote access to WMG's NSDB via API (for the scenario SDL files)
Modelling: Development of a range of high-fidelity models to be used for the purpose of the project PoC and beyond.	A comprehensive environment model of SMLL routes (A and B) in rFpro (as shown in Figure 5.1 to 5.5 as examples)
	Graphical model of (StreetDrone) Nissan eNV200 vehicle in rFpro (Figure 5.6)
	Vehicle dynamics model of (StreetDrone) Nissan eNV200 vehicle in IPG CarMaker
	Vehicle dynamics model of (StreetDrone) Nissan eNV200 vehicle in rFpro
	Traffic route model (for SMLL route A and B) in OpenDRIVE and .xml formats, for Vissim and SUMO traffic simulation. (Figure 5.7)
	SMLL route B with traffic signals from UTC SCOOT in rFpro (Figure 5.9: UTC SCOOT interface 5.8 and Figure 5.10 Route A Point cloud map generated from virtual Lidar sensor (Claytex) in rFpro 5.9)
	The project scenarios in SDL JSON files (see Appendix B, for more details)
	Synthetic point cloud data from Claytex Lidar sensor model, for localisation and path planning. (Figure 5.10)
Simulation Toolchain: Design and development of a wide range of simulation interfaces, APIs,	RTI DDS middleware for an interoperable simulation environment (Figure 5.11)
	SDL-rFpro interface (KAN Simulation Manager) via DDS
	SDL-rFpro interface (KAN Simulation Manager) standalone plug in (for WMG)

and DDS middleware for the purpose of the interoperable simulation PoC, (as shown schematically in Figure 5.11)	IPG-ASLAN interface via DDS (via ROS1-ROS2 bridge)
	rFpro-IPG interface via DDS
	rFpro-Vissim interface via DDS
	rFpro-SUMO interface via DDS
	Integrated distributed simulation environment (SCOOT-Vissim-IPG-rFpro-Claytex-ASLAN) between Millbrook and SMLL
	Integrated centralised simulation environment (SUMO-rFpro-Claytex-ASLAN) for WMG
Simulation Run: A range of interoperable simulation execution and demonstration of various interoperability options:	Testing of ASLAN autonomous driving functions, for the customer use-case, simulated with five defined scenarios at variable test conditions, including environment, with recorded results. (see Appendix B, for more details about the scenarios, also Figure 5.12 and Figure 5.13)
	Demonstration of a distributed simulation between Millbrook and SMLL, integrated with live traffic signals (UTC SCOOT) from London, traffic modelling (Vissim) at SMLL, and ego vehicle (IPG), sensors (Claytex) and AD function (ASLAN) at Millbrook (Figure 5.14 and Figure 5.15)
	Demonstration of a distributed interoperable simulation integrated with full vehicle simulator at Millbrook (Figure 5.16 and Figure 5.17)
	Demonstration of a centralised interoperable simulation integrated with full vehicle simulator at WMG (Figure 5.18 and Figure 5.19)

5.1 Millbrook deliverables and contributions

Millbrook were responsible for two elements of the delivery of the PoC in this project:

1. **System integrator**: Technical lead on the design, development, and implementation (build) of the interoperable simulation PoC.
2. **Testbed partner**: Utilising Millbrook simulation tools and assets for the purpose of the interoperable simulation PoC delivery.

Millbrook's deliverables for the project focussed on the following aspects:

1. Proposing a systematic approach for the development of interoperable simulation environments (SoS), as an end-to-end solution and toolchain for the development, test and validation of CAM systems and products.

2. The design, development and implementation of a data centric simulation architecture, based on DDS middleware, as a modular, flexible and expandable distributed interoperable simulation framework. This is used for this project and to serve as a foundation for the future advancements across CAM Testbed UK, and beyond.
3. The study of various options and solutions for the connectivity infrastructure as one of the main enablers for the simulation interoperability. Implementation of a practical connectivity solution between the testbed partners (Millbrook-SMLL and Millbrook-MFM(WMG)), for the purpose of this project PoC.
4. The development of a range of interoperable simulation models to be used by the testbed partners for the purpose of the project.
5. The development of a PoC for a simulation manager software (KAN Simulation manager), to enable a seamless integration of various scenarios (in SDL) with the distributed simulation setup and its execution.
6. The integration of ASLAN AD software with the developed interoperable simulation environment, including the development of a ROS1-ROS2 bridge for ASLAN and its interfaces with the DDS middleware.
7. The integration of the StreetDrone automated vehicle (Renault Twizy) and its onboard AD software and hardware with the Millbrook vehicle simulator, for Vehicle-in-the-Loop simulation.
8. The demonstration of a range of interoperable simulation capabilities and options, including model interoperability, simulation interoperability and distributed simulation, in collaboration with testbed partners and the customer.
9. Providing technical support to the testbed partners (SMLL and MFM(WMG)) for the integration of various simulation software and the implementation of the interoperable simulation options and demonstrations.

5.2 SMLL deliverables and contributions

SMLL’s deliverables for the project (as a testbed partner) focussed on three aspects.

1. Providing a range of background IPs, to be used by Millbrook for the development of environment, vehicle, and traffic models, for the purpose and duration of the project.
2. Providing remote access and execution of Vissim via DDS middleware (for traffic simulation), as a distributed simulation PoC demonstration (real-time co-simulation), between Millbrook and SMLL sites.
3. Providing remote access and execution of UTC SCOOT (via Vissim and DDS middleware), for traffic simulation integrated with ITS (real-time co-simulation), as part of a distributed simulation demonstration between Millbrook and SMLL sites.

The unique SMLL contributions to the simulation framework included:

a. The implementation of direct connectivity (point-to-point IPsec Tunnel) between Millbrook and SMLL sites.

b. The implementation of a data centric architecture based on DDS middleware to form a distributed simulation environment for microscopic traffic simulation integrated with traffic signals generated by UTC SCOOT. It should be noted that UTC and SCOOT are the mechanism that is currently being used to control the traffic lights in real life.
c. Demonstration of this unique simulation capacity along SMLL routes A and B.

5.3 WMG (MFM) deliverables and contributions

WMG's deliverables for the project (as the lead partner of Midlands Future Mobility) focussed on three aspects.

1. The use of the scenario description language (SDL) to define the test scenarios.
2. The integration of the National Scenario Database (NSDB) with the simulation environment and providing remote access to the scenarios through the NSDB API.
3. The development of the integrated simulation demonstration at WMG.
    d. The general framework of the interoperable simulation architecture as defined by the project team was recreated in the 3xD Simulator.
    e. The solution in the 3xD was a successful demonstration of the flexibility of the interoperable simulation framework and how it could be deployed in a standalone mode (simulation interoperability option).
    f. Note that: The 3xD architecture is isolated by design from the University of Warwick network to preserve the security of the servers, simulation environments and ultimately any sensitive data that may be created in its use during trials.

The unique WMG contributions to the simulation framework included:

a. Direct control of the vehicle model in the rFpro virtual environment from the AD algorithm using a Claytex plugin.
b. Integration of SUMO traffic simulation to run both randomised traffic as well as scenario-based scripted traffic.
c. Projection of all scenarios on the 360 degree 3xD projection system for user-in-the-loop immersion.

Figure 5.1: Cadogan Road, London

Source: Author generated

Figure 5.2: Carriage Street, London

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Figure 5.3: A206 Plumstead Road junction with Burrage Road, located outside of the SMLL Office, London

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Figure 5.4: A206 Plumstead Road, junction with Arsenal Way, located outside of the SMLL Office, London

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Figure 5.5: A206 Plumstead Road, London

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Figure 5.6: Nissan ENV200 Vehicle model

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Figure 5.7 Route A, Vissim Simulation

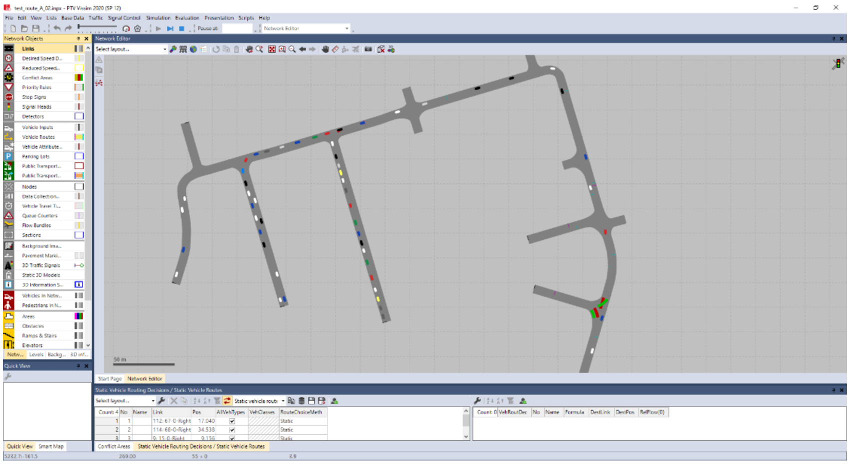

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Figure 5.8 Route B, Vissim Simulation integrated with traffic signals from UTC SCOOT

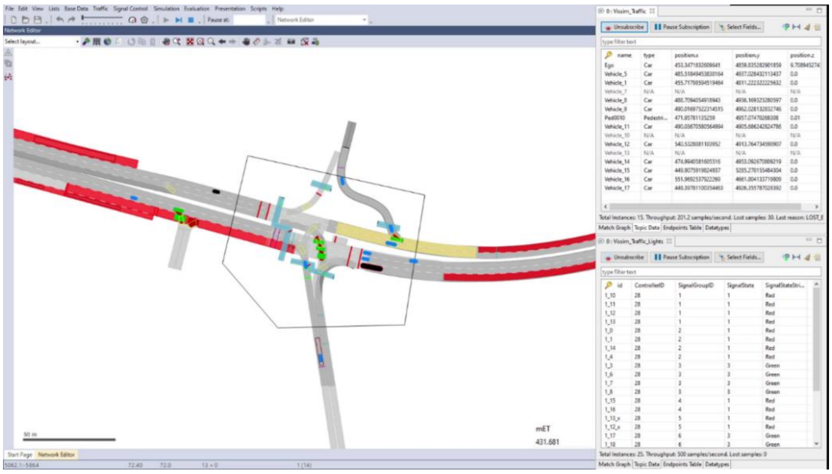

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Figure 5.9: UTC SCOOT interface

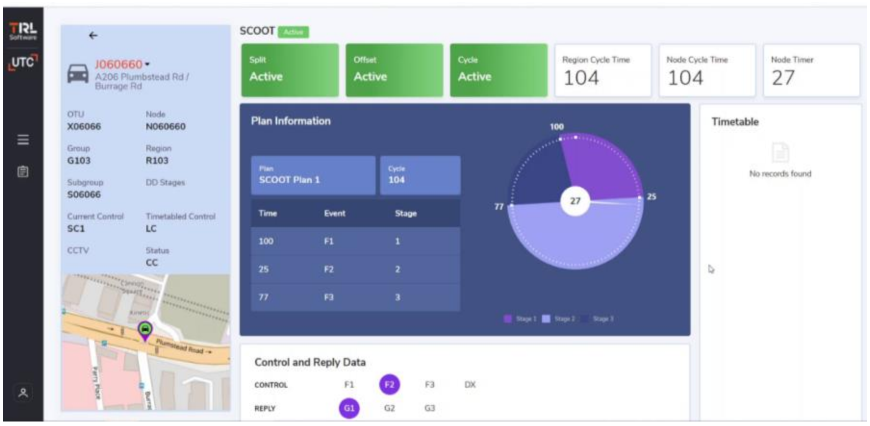

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Figure 5.10 Route A Point cloud map generated from virtual Lidar sensor (Claytex) in rFpro

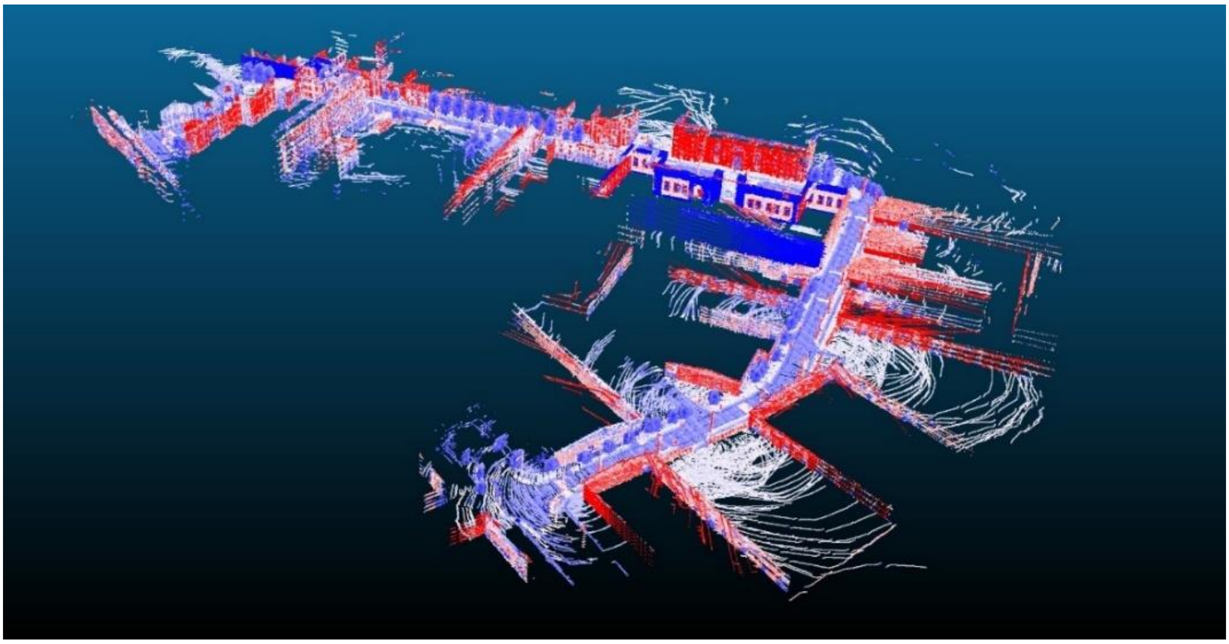

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Figure 5.11: Integrated Simulation Environment PoC

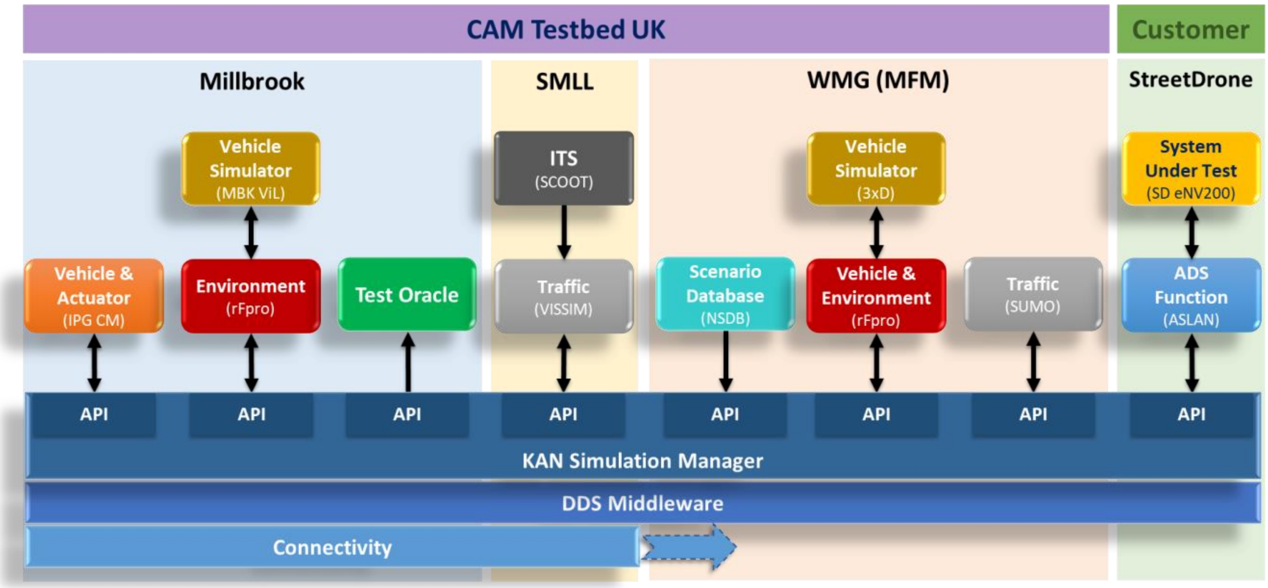

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Figure 5.12 ASLAN Perception, Planning and Control using Claytex virtual lidar sensor in rFpro (path planning)

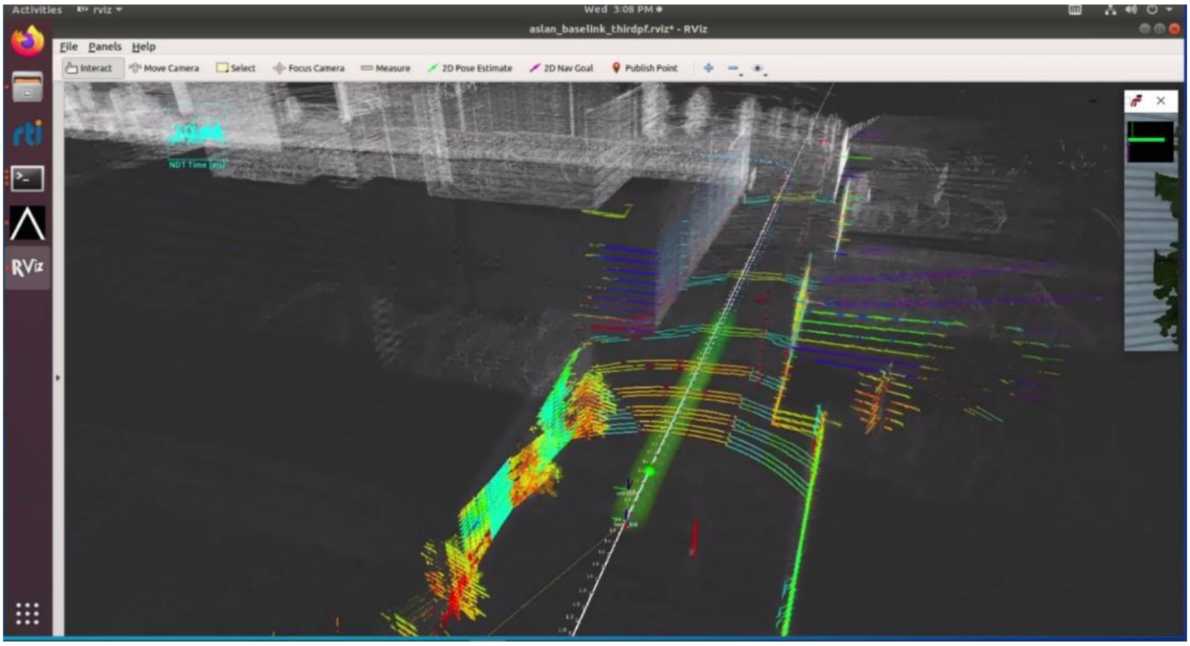

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Figure 5.13 ASLAN Perception, Planning and Control using Claytex virtual lidar sensor in rFpro (obstacle detection)

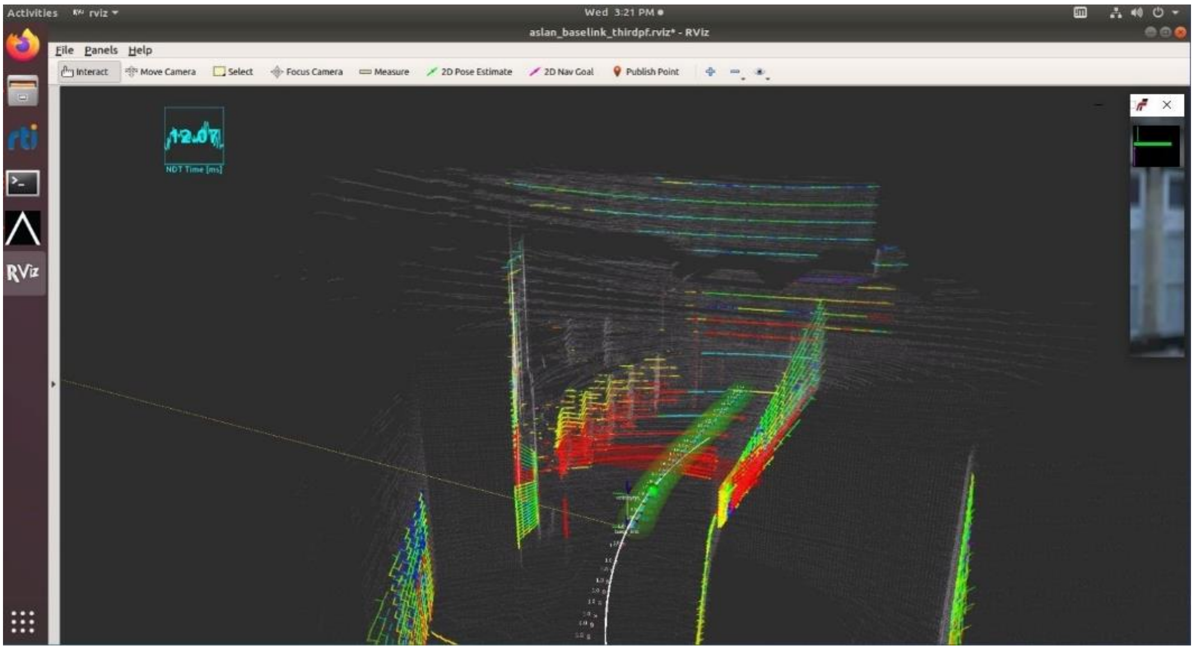

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Figure 5.14 Route A VISSIM Traffic simulation in rFpro

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Figure 5.15: Route B Traffic from SMLL VISSIM and Traffic Light Signals from UTC SCOOT in rFpro

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Figure 5.16: Millbrook vehicle simulator (Vehicle in the Loop Simulation)

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Figure 5.17: Millbrook vehicle simulator (Vehicle in the Loop Simulation)

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Figure 5.18: WMG vehicle simulator (user-in-the-loop immersion)

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Figure 5.19: WMG vehicle simulator (user-in-the-loop immersion)

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6 | Challenges and discussions

A PoC for interoperable simulation across CAM Testbed UK has been developed and demonstrated in this project. The highly innovative, collaborative, and dynamic nature of the project, highlighted the importance of:

- an agile project management system,
- transparent, trustworthy and close cooperation among the project partners, and
- a swift and effective decision-making process,

These along with the tight budget and short timeline, brought several challenges to the successful and timely delivery of the project.

During the course of the project several background and foreground IPs needed to be exchanged between the project partners who found some temporary solutions and agreement to be applied for the purpose and duration of the project.

Model interoperability

Model interoperability entitles the capability of effortless exchange of simulation assets and models between the partners. It provides a number of benefits and added value to the testbeds and their customers, including the reduction of overall cost and time for the development and maintenance of the digital assets and simulation tools between the collaborative parties.

The automotive industry is benefitting from a wide range of advanced simulation tools and software which have been developed independently over time by a wide range of well-established specialist companies. The introduction of CAVs and their subsystems and technologies in recent years, have brought a new range of simulation tools and products into the market, originating from other domains such as robotics, gaming and software.

The use of a wide range of (open-source and COTS) simulation software is one of the main challenges toward fulfilling model interoperability between the CAM stakeholders (such as testbeds, customers and system developers).

The importance of common standards and protocols to provide compatibility between the simulation packages and to enable effortless exchange of data and models between different stakeholders has been identified by the automotive (and other) sectors. As an already acknowledged challenge, several standards have been developed (or are under development) by associations such as ASAM, SAE, AUTOSAR (AUTOSAR, 2021), OMG and SISO (Simulation Interoperability Standards Organization, 2021). More specific to the domain of CAV simulation, OpenX standards (such as OpenDRIVE, OpenSCENARIO, OpenCRG, and OSI), are amongst the most recent standards that have been developed or are under development by ASAM, which have been considered in this project.

Simulation interoperability

Simulation interoperability is defined as: the capability of effortless carrying out of similar tests in different environments or drawing down capabilities for different tests.

Partners demonstrated an example of a simulation interoperability capability between Millbrook and WMG, by developing two different simulation architectures and toolchains, integrated with the same AD software and tested its functionalities with the same scenarios and use cases. This is an interesting option for customers, as it provides the opportunity and flexibility of running the same test but with two different simulation setups and toolchains, at two testbeds.

The importance of this capability, almost beyond the fact that this can be done, is that the results from each of the two simulations are considered to be valid and reproducible. This implies trust in the SoS approach which can be used for future certification by simulation. It must be a good simulation on a good simulator.

It also provides additional value for the testbed partners, to be able to share their simulation capabilities and assets and to work with the same customer or project collaboratively.

Technically, creation of interoperable simulation capacities, requires some prerequisites to be in place, including those of model interoperability. It should also be considered that different simulation tools have various level of capability, fidelity, accuracy and reliability, and are normally fit for a specific stage(s) of the development process. Some simulation tools are only capable of running offline simulations, while some others are suitable for real-time applications and HiL testing. In other words, the usefulness, suitability, and applicability of simulation interoperability should be examined and confirmed for each simulation task, according to the specific use case, and the SUT.

Distributed simulation

Distributed simulation is defined as the ability of having online (real-time) access to multiple capabilities across testbeds to allow a single test to be performed using the best-in-class from each testbed.

Distributed simulation is the most advanced and complex form of simulation interoperability, and also the most challenging and difficult one to achieve. The development of a “locally” distributed simulation system is a difficult task, but it is not too far from the current state-of-the-art. Massive Multiplayer Online Games (Achterbosch, Pierce and Simmons, 2008) is a well-developed domain of technology that enables a large number of players to participate simultaneously over an internet connection (Hampel, Bopp and Hinn, 2006), but the concept of distributed simulation is far beyond this, as it should entitle the possibility of the utilisation of multiple software with multiple users in a flexible and expandable architecture. There are some distributed simulation environments that have been developed and utilised in recent years (Brückner and Swynnerton, 2014), especially as XiL systems, but they are normally proprietary facilities, developed, owned and operated by leading OEM companies, and Tier 1s for their own development, test and validation tasks. The challenge of design, development, and implementation of a comprehensive yet flexible, interoperable distributed simulation environment between various testbeds at different geographical locations, is a significant task. This distributed simulation capability should cover a wide range of M&S tools at various levels of fidelity and be able to run millions of simulation tasks (in real-time or faster than real-time) for edge cases, as may be required by various CAM Testbed UK customers.

Such challenges for the implementation of a distributed simulation setup between various testbeds are not only technical, but also organisational and managerial. Considering the fact that each testbed is a separate business entity and has its own business strategies, policies, operations, risk tolerance, etc., there are several non-technical barriers and challenges that exist toward the implementation of such a distributed systems. Moreover, and as discussed in Section 3.4, connectivity is one of the fundamental building blocks of any distributed simulation system. Making different simulation capabilities connected, introduces some serious questions across the organisations about the safety and security of the transmitted data and IP protection; concluding cyber security and integrity as major challenges that need to be addressed in the design and implementation of a distributed simulation system across the CAM Testbed UK facilities.

7 | Recommendations for the next phase

The successful delivery of the second phase of the interoperable simulation PoC project, confirmed the technical feasibility, achievability and several benefits of interoperable simulation for CAM Testbed UK and their beneficiaries (including but not limited to: customers, certification bodies, Government and regulators). The outstanding outcomes and achievements of the project also highlighted the unique technical capabilities that exist within CAM Testbed UK in the domain of CAM M&S. These achievements signpost a number of opportunities to expand and enhance these created capabilities for a wider range of CAM Testbed UK partners and beneficiaries, as a meaningful continuation of this project, as depicted schematically in Appendix C.

This follow on project should also be considered complimentary to the other recent CCAV projects in the domain of CAM simulation, specifically: VeriCAV and OmniCAV, with the aim of providing an end-to-end solution for test and validation of CAM products and systems, in a closed-loop, distributed and interoperable simulation environment across CAM Testbed UK and beyond. This is not a trivial easy task and needs careful planning and preparation.

For the technical aspects, the project identified that invaluable expertise, experiences, and a deep body of knowledge on M&S interoperability exists in other industries such as defence and aerospace, which could be utilised, as much as possible, during the next phase of the project. Nevertheless, care should be taken to design solutions that will fit to the criteria and requirements of the automotive sector, among others, and more specifically CAM products and systems.

The valuable lessons that have been learnt, need to be reviewed and applied for future projects. The inter-organisational challenges, as highlighted in Section 6, should be addressed. A robust technical solution for the IT connectivity between the forthcoming testbed partners should be selected and implemented, meanwhile the concerns about safety and security of the data, should be addressed.

The sustainability of the developed simulation capability, and its future expansions, very much relies on the usability, benefits and added value that could be offered to industrial customers, and their acceptance and willingness to utilise these capabilities on their product development and validation. For that reason, it is recommended that the next phase of the project is conducted in collaboration with a global OEM or Tier 1 company as the project customer.

Considering the highly collaborative nature of an interoperable simulation environment, a fair, transparent and mutually agreed business model across the CAM Testbed partners is required to be developed and operated, to justify the feasibility of the future developments and investments in this domain. More details and the recommendations about the longer-term view and framework for a future operational deployment of interoperable simulation across CAM Testbed UK are provided in Section 2 of this report.

Stream 2: Role of interoperable simulation for CAM development

Professor Nick Reed

Summary

The processes for the development, evaluation and certification of connected and automated vehicles (CAVs) are immature. However, the use of virtual environments for each of these processes is likely to play a critical role. Simulation is a tool that offers developers routes to attack this problem by cost-effectively providing greater speed and flexibility of approach. This must be tempered against the critical need for simulation facilities to achieve the required level of fidelity and validity to generate useful and practical outcomes for their users. **Interoperable simulation** entails interoperability of **models** (allowing a customer to move between sites easily), interoperability of **simulation** capabilities (allowing a customer to move between sites easily to carry out similar tests in different environments) and/or **distributed simulation** (online access to multiple capabilities across testbeds to allow a single test to be performed using the best-in-class services from multiple facilities). This enables **broader and deeper testing capabilities** and **opens simulation approaches to a wider market**.

This report reviewed the potential for interoperable simulation services provided by the connected and automated mobility (CAM) Testbed UK for CAM testing and development. It was based on review and industry stakeholder engagement processes and was delivered in parallel with a related project in which CAM Testbed UK facilities delivered a proof of concept (PoC) interoperable simulation capability, that featured a demonstration with a real-world CAV developer. CAM Testbed UK consists of five physical test facilities (supported by a sixth mobility data exchange testbed) each of which operates virtual testing in some form and with the potential to be made interoperable.

Interoperability makes simulation tasks more complex by requiring distinct systems to interact in a tightly coordinated manner. However, these interactions open new possibilities for CAV testing, trialling and development that may help tackle some of the more challenging elements in this field. Particular opportunities for interoperable simulation were identified in:

- enabling a greater depth and variety of CAV safety testing;
- standardised CAV evaluations across a library of test scenarios;
- improving the cost effectiveness of CAV development;
- improving translation between virtual and physical tests of CAVs;
- enabling regulatory tests of CAV performance;
- opening the possibilities for interoperability with customers and/or collaborators beyond CAM Testbed UK.

However, there is much work to do to make interoperable simulation across CAM Testbed UK a success. Simulations must achieve the required levels of fidelity and validity to deliver credible results while standards of data sharing and connectivity between simulation components must be achieved and maintained with minimal latency to ensure successful outcomes. Cyber security risks must be mitigated without harming the compatibility of simulations with industry standard

systems to ensure appeal to the widest range of potential customers. Intellectual property rights must also be respected, ensuring data exchanges between simulation components/facilities occur under carefully managed protocols.

Recommendations identified that:

- the operating model for CAM Testbed UK interoperable simulation facilities should be to collaborate loosely (rather than be coordinated by a dedicated 'front door' organisation);
- activities should be guided and coordinated by a strategic interoperable simulation community group;
- this group would set out the strategic plan for interoperable simulation within CAM Testbed UK and ensure cooperation and alignment between its member facilities;
- marketing must attract customers with clear and coherent messaging about what interoperable simulation can achieve and how CAM Testbed UK facilities collaborate seamlessly in its delivery;
- additional PoC demonstrators would extend the interoperable simulation capabilities of CAM Testbed UK and help to generate interest in the approach.

These recommendations cannot be completed without additional investment but the market for interoperable simulation is untested. However, international competitors are ramping up potentially competing activities and there is an undoubted need for detailed simulations in the development, evaluation and certification of CAVs. By pursuing interoperable simulation via these recommendations, there is every likelihood that such an investment would generate a positive return and enable CAM Testbed UK (and associated organisations) to get a step ahead in this highly competitive market.

8 | Introduction

8.1 Task

This report is a component of Phase 2 of a larger simulation interoperability project, exploring how members of the connected and automated mobility (CAM) Testbed UK community can collaborate in offering comprehensive connected and automated vehicle (CAV) interoperable simulation test capabilities. In Stream 1 of Phase 2, members of CAM Testbed UK have demonstrated how simulation components can be made interoperable to deliver a proof-of-concept CAV simulation demonstrator.

This report is the output from Stream 2 of this project, undertaking research and engaging with key stakeholders to explore how simulation components from across CAM Testbed UK can be combined into a commercially attractive, open and interoperable simulation framework and offering recommendations for next steps.

8.2 Approach

The content of this report was developed by:

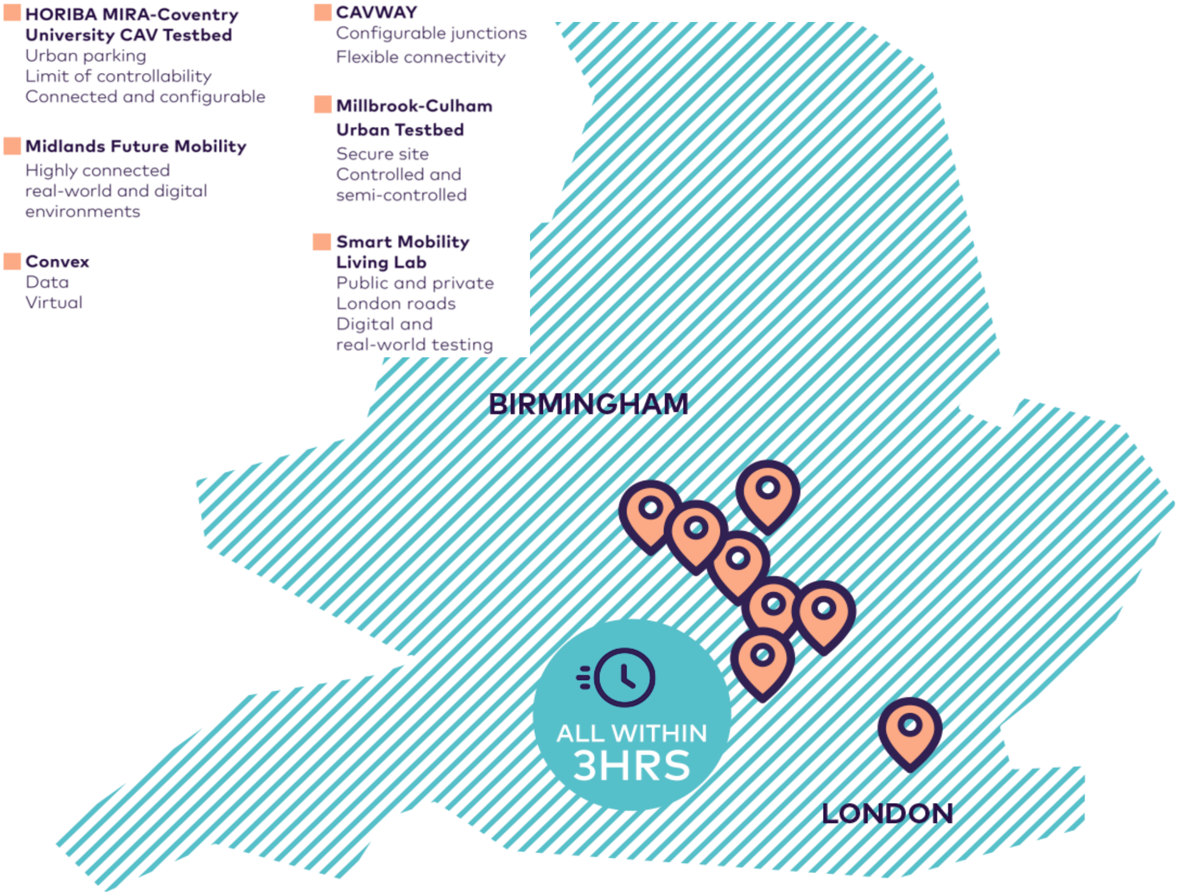
- reviewing existing commercial simulation provision for CAV development;
- engaging with relevant stakeholders from the across the UK CAM community (including representatives from the public, private, academic and start-up sectors – see Appendix D);
- integrating any emerging results from the Stream 1 PoC;
- establishing an outline business plan for the future development of an interoperable simulation capability.

The report concludes by offering recommendations for CAM Testbed UK's approach to simulation over the next five years to maximise the available opportunity that align with Zenzic's UK Connected and Automated Mobility Roadmap to 2030 ('Creation of virtual testing environment for CAM Testbed UK' milestone) (Zenzic, 2021). The recommendations consider how to ensure the simulation framework helps to enhance all the facilities within CAM Testbed UK.

8.3 About CAM Testbed UK

CAM Testbed UK is a comprehensive and integrated CAM test and development ecosystem developed under the Zenzic testbed programme. It provides testing facilities which can be used by clients to test their products and services across a wide range of use cases. At present, CAM Testbed UK comprises five physical testbed facilities, supported by a sixth facility; a mobility data exchange testbed – as shown in Figure 8.1.

Figure 8.1: CAM Testbed UK Facilities



Source: Zenzic

- CAVWAY (led by Applus Idiada)
  - Test track facility with a focus on physical testing of CAVs in road junctions.
- Midlands Future Mobility (MFM; led by WMG)
  - Real world, urban and highway environment across the West Midlands region for trialling new vehicle, technologies and services.
- Smart Mobility Living Lab: London (SMLL; led by TRL and DG Cities)
  - Real world, urban environment for the evaluation and development of CAVs across the Royal Borough of Greenwich and private roads at the London Olympic Park site.
- Millbrook-Culham Urban Testbed (led by Millbrook)
  - Private, secure road environments across two sites offering the full spectrum of controlled to semi-controlled urban environments and 90km of roads.
- Horiba MIRA-Coventry University CAV Testbed (led by Horiba MIRA)
  - Test track facility for high speed / limit handling evaluation of CAVs.
- Convex (led by Chordant)
  - Mobility data exchange facility to support CAV development.

Each facility has virtual, digital and/or data-led components with the potential for these to be made interoperable such that the testing capabilities across CAM Testbed UK are significantly greater than the sum of their parts. A review of the simulation components available across CAM Testbed UK is available in Appendix E and more information on the individual facilities is available on the Zenzic website[4].

8.4 Stream 1 deliverables

Stream 1 of the project was delivered in parallel to Stream 2 and led by Millbrook with support from members of CAM Testbed UK. It has delivered a multisite, interoperable simulation PoC to demonstrate the potential value of such collaboration. The intention was to source simulation components from across CAM Testbed UK (more details are available in Section 4 & 5).

Data from these components was shared using a Data Distribution Service (DDS) as a middleware platform to offer a user (CAV developer, StreetDrone) an interoperable simulation capability in which to test their automated driving system (ADS).

This report has used learning derived from Stream 1 activities as one of the inputs to inform the potential for interoperable simulation across CAM Testbed UK as a collaborative commercial offering to the CAM sector.

[4] https://zenzic.io/testbed-uk/

9 | Why simulate

9.1 What is simulation

The BSI (2020) CAV Vocabulary defines simulation as:

"Computer generated environments used to test components, systems or human behaviours."

This definition recognises that the application of computer technologies in modelling and evaluating automated vehicle systems and behaviours has very broad relevance from the simulation of individual components within a vehicle through to the simulation of city-scale mobility systems. Simulations can be conducted in real-time or offline depending on the application. It is important to recognise that simulation is not an endpoint but is a tool that supports development or understanding of a system. In this report, simulation was considered in the context of potential services that could be offered to the CAM market by achieving interoperability of simulation capabilities across CAM Testbed UK.

9.2 The benefits of simulation

Computer-based simulation emerged as an effective tool for exploring complex scenarios as processing power increased. By comparison to real world tests, the value of simulation lies in being able to test or investigate situations:

- faster, more extensively and more repeatably;
- that could be considered rare, dangerous, costly and/or otherwise impractical;
- in distant locations without needing to travel;
- without being limited by daylight or environmental conditions.

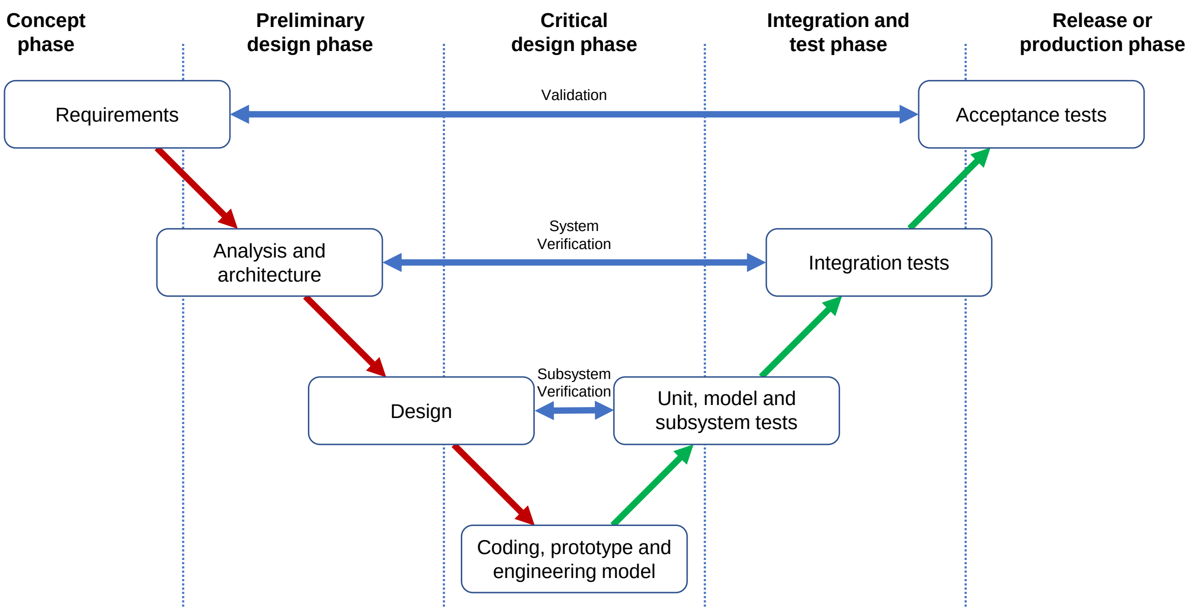
The use of simulation tools may also offer more (and more precise) data about the test conditions than can be accessed in real world tests and trials.

Importantly, effective simulation can help in understanding and mitigating risks or challenges associated with deployment of a system, process or operator, providing confidence in their reliability and/or safety in the real world. A well-known example of this is in commercial aviation, where a trained pilot can become certified in an alternative aircraft (type training) entirely by using a suitably specified flight simulator (European Commission, 2011).

Simulation and the V-model

System development procedures in engineering often follow a series of steps that have come to be known as the V-model (see Figure 9.1). A concept is developed and designed in the steps descending on the left side of the 'V' (red arrows); the resultant prototype is tested and refined increasingly stringently in the steps ascending on the right side of the 'V' (green arrows) as the system approaches full deployment readiness. Verification and validation of the performance of the system against the original specification and design criteria are performed at each stage (blue arrows).

Figure 9.1. Engineering 'V' diagram showing system development lifecycle



Source: Adapted from Fowler (2014)

The development of CAM is yet to reach maturity and there is global competition to deliver products than can access the anticipated commercial and transportation benefits of CAM. Well defined and validated simulation approaches may help progression through the V-model for the development of CAM, accelerating the transition from one step to the next and ultimately delivering the anticipated benefits (and commercial advantage) more quickly. The value of simulation in achieving this is particularly important when the cost of developing advanced automated functions is taken into consideration. A prominent company developing advanced driver assistant functions predicts the effort to develop validation environments for highly automated vehicles 10–20 times higher than the effort to develop the vehicle automation function to be validated. The ratio increases for fully automated vehicles to 20–50 times higher (Paulweber, 2017).

Progressing through the V-model places different demands on simulation fidelity. At the conceptual stage, highly detailed simulation is less important as the developer is interested in understanding whether the proposed system satisfies basic principles of engineering. As the system matures, simulation fidelity becomes much more important as the developer seeks to validate that the system under development delivers the safety and performance characteristics set out in the design and to build confidence that the system will meet any required acceptance or certification criteria when completed. Issues of simulation fidelity, veracity and validity are further discussed in Section 9.4.

Confidence in the safe operation of CAVs is particularly important since the behaviour of a CAV is safety critical to its occupants and the environment through which it is driven. In recommendations to the European Commission, Bonnefon *et al.* (2020) noted that a minimum expectation on CAVs is, to be considered ethical, that they should reduce physical harm to persons. However, Kalra and Paddock (2016) estimated that CAVs would have to be driven hundreds of millions of miles and sometimes hundreds of billions of miles to prove their reliability in terms of fatalities and injuries relative to current traffic safety performance. Validated simulation environments offer a route to achieving such numbers without the practical problems of testing enough CAVs for a sufficient time and in a suitable variety of weather, traffic and geographical environments to provide that statistical evidence.

Simulation and CAV development

Simulation is likely to be an essential element of the CAV development process:

- For **CAV component developers** (e.g. automotive Tier 1 suppliers):
    - Component-scale simulation allows testing and development of components as part of a complete automated driving stack without needing to develop a whole automated vehicle (or without accessing one from another organisation).
- For **CAV developers** (e.g. vehicle manufacturers or technology developers):
    - Vehicle-scale simulation allows testing of the performance and behaviour of their CAVs in a wide range of challenging traffic situations without needing to drive sufficient miles (potentially billions; Kalra & Paddock, 2016) needed to encounter such challenges in the real world.
    - Human-in-the-loop simulation allows testing of how human drivers, operators and other road users engage with and respond to the behaviour of CAVs and automated driving systems.
- For **CAM operators/transport authorities** (e.g. transport service providers or city/local/highway authorities):
    - City-scale simulation allows the assessment of the impact of CAM on the transport ecosystem and evaluation of potential business models of CAM operation.
- For **CAM regulators** (e.g. national transport authorities or vehicle performance certification agencies):
    - To provide independent and certified evidence that a CAV operates in a safe and appropriate manner in the operational design domain in which it is intended to be deployed.
    - To give confidence to residents and businesses on how CAM will deliver benefit to communities in terms of efficient provision of transportation.

This report considered how capabilities from CAM Testbed UK may be successfully integrated to deliver simulation applications across these domains and what challenges may be faced in creating a compelling proposition for the commercial market.

9.3 Interoperable simulation

The focus of this report is **interoperable simulation** since previous work identified this as the most promising approach for exploiting the various simulation capabilities and testing facilities available across the CAM Testbed UK ecosystem. Interoperability of simulation capabilities allows various configurations of simulation offered by organisations from across the ecosystem to be joined and thereby offer a greater level of simulation capability, a wider range of tools to the market and help smooth the transitions between simulated and real-world testing. This flexibility is vital since the technologies, protocols and tool chain for CAV development and operation are not yet mature.

Interoperability is generally defined as the ability of different systems, devices, applications or products to connect and communicate in a coordinated way, without effort from the end user (Lewis, 2019). In the context of interoperable simulation, this means that different aspects of the simulation of a system or process may run on distinct systems, between different organisations and/or in different locations. This could include the exchange of data, models, protocols, tools and/or standards. Interoperability therefore relates to the ease with which such simulations can be coordinated and delivered.

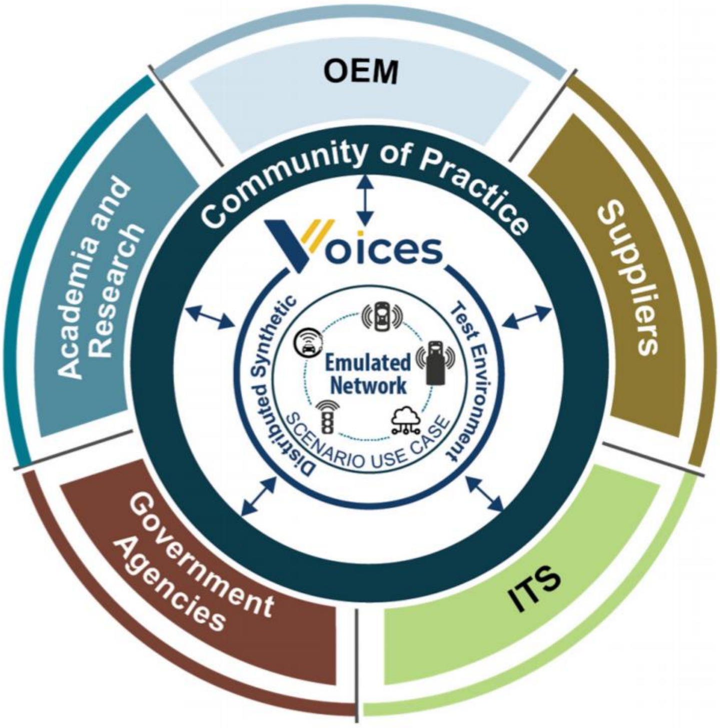
Three modes of simulation interoperability were defined by Zenzic and considered for this project:

- **Interoperable models:** Models across sites are in an interoperable format which allows a customer to move between sites easily.
- **Interoperable simulation:** Simulation capabilities across sites are in an interoperable format which allows a customer to move between sites easily to carry out similar tests in different environments or draw down capabilities for different tests.
- **Distributed simulation:** Online access to multiple capabilities across testbeds to allow a single test to be performed using the best-in-class services from multiple facilities.

Beyond technical integration, an important aspect of interoperability for CAM Testbed UK is the effectiveness of cooperation between the member facilities in delivering distributed simulation services. Having aligned under the CAM Testbed UK banner, participating organisations must ensure that collaborative projects involving interoperability of simulation facilities present coherent and consistent services to customers and interact smoothly and successfully in delivering the required outcomes.

The importance of simulation interoperability is highlighted by the U.S. Department of Transportation's Virtual Open Innovation Collaborative Environment for Safety (VOICES) project (USDOT, 2021). This is a $10m, two-year study to create a PoC of a distributed virtual platform for stakeholder collaboration in a virtual environment for research, with an initial focus on connected and automated driving research. An overview of the project is provided in Figure 9.2.

Figure 9.2: Overview of the VOICES project (ITS: Intelligent Transport Systems; OEM: Original Equipment Manufacturer).



Source: USDOT, (2021)

The activities in Stream 1 (PoC) and Stream 2 (this report) of the current Zenzic project have positioned the UK well to collaborate with the VOICES initiative. In particular, Stream 1 demonstrated how to achieve interoperable simulation using a particular protocol – it would be of interest to work with VOICES to ensure that the interoperability approaches applied within this project align with their ambitions and the use cases planned for VOICES (and if not, how would they need to be adapted to ensure international alignment on interoperability).

9.4 The challenges for simulation

The critical challenges for simulation are its fidelity, verification and validity (: Feinstein & Cannon, 2001):

- **Fidelity** means the extent to which a simulation replicates reality;
- **Verification** means the extent to which the model is operating as intended;
- **Validity** means the extent to which conclusions reached from simulation testing are similar to if the same tests were conducted in the real world.

Low fidelity simulation can be perfectly acceptable if it operates as expected and delivers valid outcomes. An example would be a driving simulator may have low face validity[5] (see Figure 9.3 – (a)), using off-the-shelf vehicle controls and standard computer systems. This may be perfectly suitable for demonstrating a new road layout to drivers but would be inappropriate for examining drivers' visual behaviour at junctions due to the limited visual field of the simulation.

The high face fidelity simulator system (Figure 9.3 – (b) the University of Warwick 3xD driving simulator) uses a real vehicle and has a 360° horizontal visual field and is therefore more appropriate for studies examining driver visual behaviour or drivers' interactions with in-vehicle systems. Even though the two systems may be running the same simulation software, the applications of each are different. It is therefore vital that an appropriate level of simulator fidelity is selected for any research, development, validation or certification activities. For interoperable simulation, validity must be considered for the individual components contributing to an interoperable system and the complete system as a whole to ensure that results achieved are truly representative of the situation of interest.

Figure 9.3: Examples of (a) low and (b) high face fidelity driving simulators

(a) Low face fidelity driving simulator **(b) High face fidelity driving simulator**

Source: Author generated

Verification is the process of checking that the simulation code and subsystems are behaving as planned. Validation is the process of checking that the simulation produces results that coincide (or at least correlate) with how that simulated situation would develop in the real world. A key reason for the use of simulation is that it reduces the costs, timescales and/or risks associated with undertaking trials of technology – failure to verify and validate simulations sufficiently may produce incorrect and potentially misleading results, wasting time, money and introducing new risks.

[5] Face validity refers to the degree to which a simulation appears like the real situation

Further challenges for interoperable CAV simulation are described in Section 11.

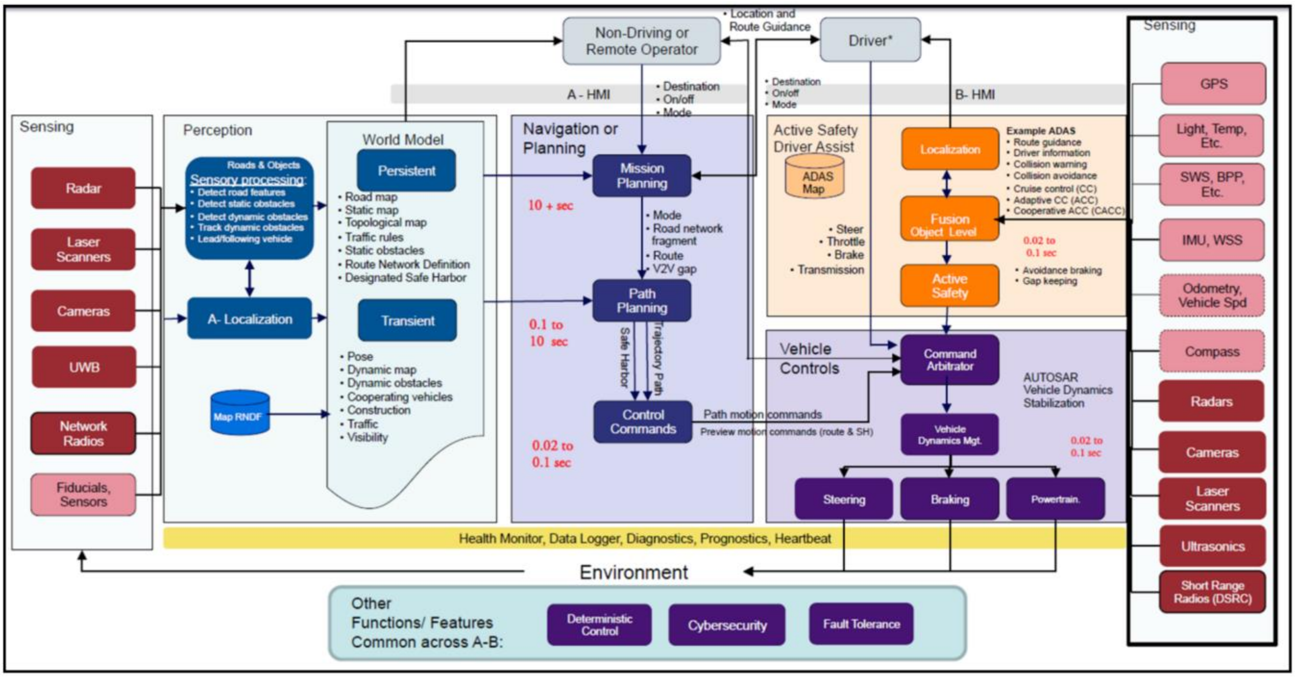
10 | Simulation for CAVs

A CAV is an assembly of components (such as sensors, wheels, electronic control units etc.) and sub-systems (such as propulsion, steering, suspension etc.) brought together to operate as a single entity that operates in an environment as part of a wider traffic and transport mobility network. Each of these layers brings opportunities for simulation by bringing together simulation components from across CAM Testbed UK.

10.1 Simulation of CAV sub-systems

SAE (2016) presented an outline architecture for automated driving systems in their J3131 standard. The flow diagram for this architecture is shown in Figure 10.1.

Figure 10.1: SAE International Autonomous Mode Functional Architecture Flow Diagram



Source: SAEJ3131 (2016)

Individual boxes within this architecture each represent an element of CAV operation that could be simulated – for example, the behaviour of radar (Chipengo, 2018) and laser scanner (Manivasagam *et al.*, 2020) sensors. Acting within a full CAV simulation, this ability to exchange simulated sensing modules would allow a sensor developer to understand how their system behaves and how it compares to alternative systems. Such modular simulations may also allow a CAV developer to compare how different sensor types might improve the relative performance of their complete system – for example, comparing the performance of using solid state lidar against mechanical lidar systems.

10.2 Simulation of a CAV as a complete entity

Rather than simulating component subsystems, an organisation may be interested in simulating the complete behaviour of a CAV. This could be for many reasons – to understand the behaviour of a new prototype, to test a control stack in a new environment, to evaluate performance in a specific range of weather conditions and so on. To achieve the required simulation fidelity, the simulation of a complete CAV may require embedded simulation of CAV subsystems – for example, it may require embedded simulation of the sensor systems to ensure that the output of the complete automated driving system delivers a genuine representation of how the complete CAV would behave in the real world.

10.3 Simulation of a CAV for exploring human interactions

Driving simulators that allow human participants to operate a car in a virtual environment have been used for decades. They are employed for a wide variety of tasks, allowing participants to:

- experience situations that may be considered too unsafe or too impractical to create on a test track or public road;
- drive in environments that have not yet been created in the real world to evaluate infrastructure design;
- drive in impaired states to assess, for example, the effect of mobile phone use on driving performance;
- use new human-machine interface (HMI) designs for ergonomic assessment;
- experience new vehicle technologies in development.

As an example, the UK is well served for driving simulators with high fidelity systems operated by numerous organisations – examples are shown in Figure 10.2.

Figure 10.2. Examples of UK driving simulators

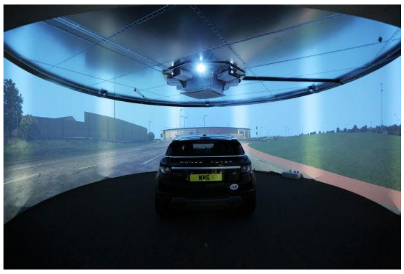
(a) University of Leeds Advanced Driving Simulator (LADS)

(b) TRL DigiCar

(c) University of Southampton driving simulator

(d) Millbrook driving simulator

(e) University of Nottingham driving simulator



(f) University of Warwick 3xD driving simulator

Source: Author generated

As can be seen from the images, the simulators feature real vehicle cabins surrounded by graphics displays to provide the vehicle occupant with a realistic view of the driving environment. Some driving simulators use motion cueing to enhance feelings of realism. Of those shown in Figure 10.2, it is simulator (a), the University of Leeds Advanced Driving Simulator (LADS), which has the most sophisticated motion platform, providing eight degrees of freedom of movement. The Millbrook driving simulator and the University of Warwick 3xD simulator, shown in Figure 10.2(d) and(f) respectively, are of interest as they allow different vehicles to be situated within the simulation chamber. This means that a CAV developer can potentially bring their own vehicle into the simulator facility for testing.

Such driving simulators are particularly useful for exploring how human participants respond to emerging vehicle automation systems before they are introduced to real roads. For example, many studies have explored responses to transitions between human and automated control and back (e.g. Gold *et al*., 2013; Merat *et al*., 2014; Maggi, Romano & Carsten, 2020). Other studies have used driving simulators to examine interface design for CAV control systems (e.g. Morra *et al*., 2019; Voinescu *et al.,* 2020).

10.4 Simulation of CAV Hardware-in-the-Loop (HiL)

While simulation can be used to model the performance of individual subsystems of CAVs, it is also possible for simulation to provide a test environment for real CAV subsystems, using what is known as Hardware-in-the-Loop (HiL) simulation. The simulation model provides the inputs to the CAV hardware and the resultant outputs from the hardware feed back into the simulation. An example would be an electronic control unit receiving simulated sensor inputs and outputting signals to simulated actuators (e.g., Gelbal *et al.,* 2017). This allows rapid iteration of hardware systems without the additional complexity of having to install each new version safely in a real vehicle.

10.5 Simulation of environments to test CAV behaviour

Testing of CAV systems in accurate simulations of environments allows CAV developers to build virtual experience of new road systems before testing their CAVs in the real world. This can help the developer to understand where their CAV system may encounter difficulties and where specific risky behaviours may need to be modified. Simulation can also be used to understand how the presence of CAVs affects network performance. By integrating CAV control algorithms into microsimulation models, it is possible to explore the extent to which CAVs affect congestion levels based on their driving behaviours and presence in traffic.

Furthermore, simulation allows organisations to explore how CAVs respond to traffic situations that are not frequently encountered in real world driving. For example, it is possible to 'inject' data captured from the behaviour of real humans into simulations to enable CAVs to detect and respond to their actions. This means training of CAV algorithms can be made more thorough and more efficient by exposing them to a wider range of situations based on real data.

A further use case for CAV simulation is in understanding how commercial models of CAV deployment might develop. For example, a mobility service provider may seek to understand how a variety of vehicle form factors and operating regimes of CAVs perform when working as automated taxis in an urban environment. Simulation would allow them to understand the commercial implications of such models (critically important to CAV operators) and their potential impact on the use of public transport services (critically important to local authorities).

11 | Delivering interoperable simulation

11.1 Benefits of interoperable simulation

General

By bringing together systems, models, data, technologies and/or organisations, interoperable simulation may permit the more thorough analysis of a complete system or process. Note that not all components of an interoperable simulation need to be virtual. For example, a simulated vehicle model operating in a virtual traffic scenario could send vehicle control inputs to a real vehicle on a chassis dynamometer allowing the mechanical implications of the simulated vehicle model to be evaluated. This can be framed alternatively as offering potential cost savings – interoperability may allow testing, trialling and development to proceed more quickly, using fewer resources and with reduced maintenance costs. Interoperability depends fundamentally on facilitating interactions between elements of a system. This can make access to information simpler and easier for all appropriate stakeholders in the testing and development of a system.

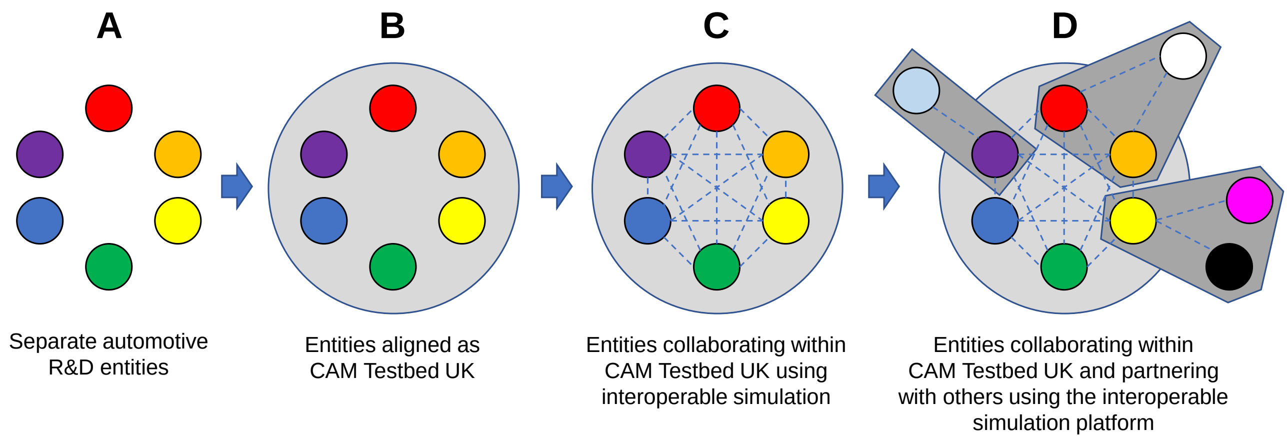
For CAV development

The technologies for delivering safe and effective CAV operation are yet to be established. Consequently, the resources, protocols and tools for evaluating these technologies are similarly immature. With a long history in automotive development and innovation, the UK has a broad set of organisations and facilities that are relevant to this task. This was recognised and enhanced by Zenzic in creating CAM Testbed UK, with the vision for a cohesive suite of independent facilities that offer a comprehensive range of research, testing, trialling and certification facilities to the CAM sector.

As noted in Section 8.3, each facility within CAM Testbed UK includes some form of capability for simulation and virtual testing. By making these capabilities interoperable, the scope of activities that can be delivered by CAM Testbed UK is widened. For example, an organisation testing the dynamic performance of its vehicle at a proving ground facility may be able to extend that testing seamlessly by evaluating its performance in a simulated urban environment at another of the CAM Testbed UK facilities.

Increasing the openness of simulation facilities to interoperability within CAM Testbed UK has the added benefit of increasing the accessibility of those facilities to external organisations. This has two distinct advantages. Firstly, that it enables customers to engage with facilities using the protocols established for interoperability – for example, a Japanese OEM could test CAV models on urban streets using interoperability protocols and live connections to a simulation facility in CAM Testbed UK. Secondly, it enables facilities beyond CAM Testbed UK to participate in collaborative simulation activities. For example, many universities have advanced simulation capabilities relevant to CAV R&D; where relevant, these capabilities can be incorporated into CAM Testbed UK simulation services to meet the needs of a specific project or customer. This progression is illustrated in Figure 11.1.

Figure 11.1. Illustration of how interoperability can connect facilities within CAM Testbed UK and enables external engagement



Source: Author generated

Figure 11.1(A) illustrates the six independent test facilities that existed prior to CAM Testbed UK being established. Zenzic aligned those six facilities under the CAM Testbed UK banner, shown in Figure 11.1(B). They still operate independently but work towards a common vision of CAM testing and development in the UK with simple and straightforward protocols established that enable customer organisations to work with multiple testbeds. (C) illustrates the facilities collaborating as CAM Testbed UK using interoperable simulation to offer new services to the market (as in Stream 1 of this project). Finally, Figure 11.1(D), shows the CAM Testbed UK facilities collaborating with each other and external organisations/customers using the interoperable simulation platform.

Further collaboration and co-operation between CAM Testbed UK facilities through interoperable simulation should also help customers of those facilities to discover additional capabilities for CAM R&D across CAM Testbed UK. This should help to secure more foreign inward investment, stimulate growth of UK-based developers and reinforce the business case for the CAM Testbed UK facilities.

11.2 Validation and verification

The validation and verification of a simulation are vital in having confidence that the results generated are sufficiently representative of real-world performance. Whilst validation and verification are important for individual simulations, the challenge is further extended by making simulations interoperable. Confidence is needed in the validity and veracity of both the individual component simulation systems and the complete simulation unit created by making systems interoperable. Providers supporting interoperable simulation will need to be able to offer verification and validation evidence of their individual components contributing to the complete system and an understanding of how any potential errors may be propagated by connection of the interoperable simulation components. A suitably valid and verified simulation can be used in the verification and validation of a system or process in progressing through the engineering V-model (see Figure 9.1).

11.3 Quality of Service

A variety of topics related to interoperable simulation can be collated under the term 'quality of service' (QoS)[6]. This relates to the success with which the elements of an interoperable simulation are brought together and function as a useful, reliable and secure system.

Data sharing and connectivity

Fundamental to effective interoperability is data sharing. This must be achieved reliably and securely at a latency level that is within acceptable performance criteria, including (where relevant) appropriate real-time scheduling and time synchronisation. Accurate simulation often depends on the timely exchange of data and, for the modelling of some systems (e.g. dynamic braking behaviour), a data frequency at the millisecond may be required. Huge multiplayer online driving games show that this is achievable at scale.

For the connectivity of interoperable simulation, there are two critical aspects that must be considered. These are:

- **networking infrastructure** – the routes by which data is exchanged between collaborating sites and,
- **simulation integration** – the ways in which data is shared between components of the interoperable simulation.

For network infrastructure, it is essential that the data links between elements of the simulation are capable of handling the volume, speed, accuracy and security of data being transferred in order to maintain the integrity of the simulation. This must be maintained irrespective of the medium of transfer (e.g. 5G cellular network, WiFi, Bluetooth etc.) and/or the distances involved (e.g. whether interacting simulation components are in the next room or in another country).

For simulation integration on an ad hoc basis, bespoke APIs (application programming interfaces) may be sufficient, enabling defined interactions between computer systems. However, the vision for CAM Testbed UK is to be able to offer multiple simulation systems to be connected **reliably** (consistent bandwidth and latency), **flexibly** (different combinations of simulation facilities needed per project) and **dynamically** (different simulation performance requirements needed per project). Developing a library of APIs to cover all possible permutations of interoperable simulation is impractical. However, these requirements are addressed by application of the data distribution service (DDS) standard, first published by the Object Management Group in 2004 (see Pardo-Castellote, 2003). This is a middleware protocol and API

[6] Note that data distribution service (DDS) providers offer their own definition of quality of service – for example, around fifty QoS policies for DDS from RTI: http://community.rti.com/rti-doc/500/ndds.5.0.0/doc/pdf/RTI_CoreLibrariesAndUtilities_QoS_Reference_Guide.pdf

standard for connectivity that integrates system components, providing low-latency, reliability, security, synchronicity and scalability.

The DDS approach allows data produced on one system to be made available everywhere across the DDS domain, according to defined and controlled data sharing mechanisms – thereby tackling connectivity issues but also ensuring that organisations have control over information shared as part of an interoperable simulation, giving confidence over IP protection to both testbed and customer organisations. Commercial developers apply the DDS standard to support organisations in connecting distributed systems. This type of middleware approach seems to be a good fit for the requirements of interoperable simulation across CAM Testbed UK.

An example of interoperable simulation systems using DDS middleware

Brummett *et al*. (2020) described an example of a DDS-based interoperable simulation system for evaluating civilian and military radar systems. The authors recognised five key advantages of the approach:

- Modularity: components can be independently updated or replaced without affecting the rest of a system.
- Reusability: software is reusable at the component level.
- Interoperability: Well-defined ports and standardisation ensure interoperability between distributed applications.
- Extensibility: a component-based architecture is inherently loosely-coupled, supporting easier extensibility of component and system functionality.
- Reduced complexity: encapsulation, modularity and separation of concerns help to reduce design-time and run-time system complexity.

It is worth noting that the Convex mobility data exchange is part of CAM Testbed UK and may be a useful resource for acquiring data for use in simulations. However, at least in its earliest incarnations, Convex is unlikely to be suitable as the platform for the low latency, high bandwidth data exchanges required for interoperable simulation.

Discussions with stakeholders indicated that, for some applications (especially vehicle dynamics), latency was recognised as one of the key challenges, particularly in the context of DDS, where the data distribution layer could act as an additional source of latency. However, DDS providers are finding ways to address this challenge through code that bypasses unnecessary steps in the communication process. For example, in efforts to reduce DDS latency for a racing application, RTI achieved up to a 98% improvement in performance sending a pointer to a data location rather than copying the data to a new location (see Puthuff, 2021). In addition to massively reduced latency, this approach has the benefit that latency is unaffected by data size as it is only the small (and consistently sized) pointer to the data location that is being sent.

Cyber security

CAV development is a critical and highly sensitive topic for the vehicle manufacturers, technology organisations and research bodies involved in the domain. All contributors involved in CAM Testbed UK are familiar working with such organisations and recognise that ensuring data security is vital. As a result, each organisation has extensive IT security protocols to protect internal and customer data and prevent external data access. However, cross-facility connectivity is required in order to achieve interoperable simulation. The first hurdle to overcome in delivering secure interoperable simulation is therefore the management of connectivity and data exchange protocols between organisations within CAM Testbed UK to ensure timely and flexible communication of data without compromising security. Recognising that an interoperable simulation can only be as secure as the weakest link in the complete system, the services provided by CAM Testbed UK needs to be flexible to address the needs of a diverse range of customers rapidly and effectively whilst being secure to potential accidental or malicious data loss.

It should be recognised however that cyber security is a critical aspect of CAM and simulation will be an important contributor to managing cyber-risk. Interoperable simulation services offered by CAM Testbed UK could enable organisations to explore the potential impact of cyber security attacks and the effectiveness of mitigations.

Compatibility

Whilst a DDS platform can facilitate the timely sharing of relevant data streams, a clear challenge of interoperable simulation is ensuring such streams are compatible across different components of the system. For example, a visual database available from one member of CAM Testbed UK may not be compatible with the driving simulator used by another. This becomes more complex when dealing with customers who may use unusual or proprietary formats and software. The interoperable simulation needs to be flexible to the common data and software formats in order to offer the most comprehensive simulation services and to accommodate the needs of the widest range of customers. Discussions with stakeholders identified the following non-exhaustive list as representing key software platforms and technologies that should be accommodated within the CAM Testbed UK interoperable simulation capability:

- Aimsun
- ASAM OpenDRIVE
- Autodesk 3DS Max
- Autoware
- CARLA
- CarSim
- IPG CarMaker
- Matlab Simulink
- nVidia DRIVE
- PTV Vissim
- rFpro
- Road XML

- dSPACE
- Eclipse SUMO
- Unity
- Unreal Engine

11.4 Suitability and flexibility

When devising an interoperable simulation approach, it is important to determine which are the components that are strictly necessary to share and which offer incidental benefit to deliver on the customer requirement. For example, an organisation seeking to understand the dynamic performance of their CAV may be less interested in the accuracy of the graphics that create any visualisations compared to the accuracy of the dynamic behaviour of the vehicle; an organisation interested in simulations of CAVs operating as a fleet across an urban area may be less interested in precise sensor modelling compared to the accuracy of the movement of the vehicles in traffic around the simulated routes serviced by the operation. The organisations providing interoperable simulation across CAM Testbed UK will need to understand how their offerings bring value to the process, how they can collaborate to offer new services and how to charge customers for that accordingly.

11.5 Intellectual property

The goal of interoperable simulation for CAM Testbed UK is for organisations to bring CAM systems or concepts for commercial testing or development using the available simulation systems across the community. The nature of this work is that it is often highly sensitive with developer organisations seeking to protect their intellectual property. A key challenge for simulation services based on sharing of data is to ensure that only information necessary for accurate simulation is shared. Often, this could mean that a third-party system under test acts as a 'black box' such that the simulation providers have no knowledge of how data is being processed – all that matters is that the correct inputs are provided and the correct outputs are received in order for the simulation to proceed correctly. The developer and testbed organisations can then have confidence that their intellectual property (IP) is protected appropriately. All organisations within CAM Testbed UK frequently work with organisations and on projects that manage sensitive IP issues – the same rigour and security needs to be applied across interoperable simulations involving critical IP.

11.6 Target market

An issue for any proposition coming to market is defining the customer profile. For CAM development, there are a broad range of potential customers from niche start-ups through to multi-billion-dollar technology companies and vehicle manufacturers. Many established CAV developers have created (or acquired) in-house simulation capabilities. For example, Waymo (2020) reports driving 20 million miles per day in simulation to expand the scale and complexity of their automated driving experiences – Waymo also acquired UK start-up, Latent Logic, in December 2019 to improve the complexity of simulated driving behaviours. To attract such large organisations will require CAM Testbed UK to be able to offer unique capabilities through the interoperability of components offered across its members at a competitive price that does not lead such customers to consider developing that simulation capability for themselves or elsewhere.

Conversely, CAM Testbed UK should also provide simulation services for start-ups and research organisations that are developing CAM systems but do not necessarily have the resources to access simulation capabilities of their own. Again, interoperable simulation services need to be keenly priced and accessible by such organisations in order for them to select CAM Testbed UK for their R&D programme.

In terms of customer size, the sweet spot for CAM Testbed UK interoperable simulation is scale-up organisations that are successful in their specific market but are seeking to expand or derive additional evidence about the performance of their systems and do not have the (financial or human) resources to develop their own simulation capability. To deliver for such organisations, CAM Testbed UK will need to be able to show that interoperable simulation services offered will genuinely accelerate their product development processes and can deliver according to their specific time and resource requirements, which may be critical in terms of future product launches or investment rounds.

Finally, there is a powerful case for interoperable simulation if virtual testing is a critical element in official CAV safety assurance and certification. Large, interconnected facilities may be needed to determine the level of sophistication and fidelity required for simulations to provide the required assurance in CAV safety. Depending on how certification processes emerge, CAM Testbed UK may be able to capture a significant proportion of the market for certification testing and/or pre-certification development.

11.7 Operational oversight

Interoperability introduces technical challenges in coordinating and communicating data between simulation components. However, an additional set of challenges arises when managing the commercial and administrative processes associated with delivering interoperable simulation, particularly when this involves multiple organisations.

The precise engagement model for how organisations operating interoperable simulation facilities should interact with customers must be agreed and understood. This should clarify which organisation is the lead partner and how fees for use of the interoperable simulation (and any components therein e.g. visual databases, traffic models etc.) are to be allocated between the organisations involved. Similarly, as each organisation involved is likely to be involved in independent projects using the simulator facilities, a suitable booking system will be required to ensure all necessary components are available at the required time. Furthermore, a system for flexibly managing service delivery may be required in the event that a specific component of the interoperable simulation is unavailable at the required time due to unforeseen circumstances (e.g. due to a technical fault, communications issue etc.).

These issues are not relevant for the activities in Stream 1 where the focus is demonstrating interoperability of simulation and many of the challenges can be addressed by bespoke bilateral agreements between participating organisations in the context of the project. The challenge will emerge when CAM Testbed UK is offering services to the market that need to meet the requirements of clients rather than be tailored to a specific PoC.

In the military domain, simulations across the land, sea and air services are coordinated through the Defence Simulation Centre (DSC) Funded by the Ministry of Defence, this acts as a 'front door' for simulation service providers and for those seeking their services (see Appendix F). Military simulation activities are guided by a number of standards, primarily JSP939 (see Appendix G), supported by dedicated technical experts within each branch of the military and enforced by the chain of command. By contrast, the automotive sector does not have the hierarchical structure nor consistency of business model and customer that characterises military simulation, making direct translation of the DSC model to CAM Testbed UK challenging.

Numerous potential models of operation for the management of CAM Testbed UK interoperable simulation services were discussed over the course of the stakeholder engagement process. These fell into one of three categories reviewed below.

Zenzic lead

Since Zenzic is responsible for coordinating the strategy around CAM Testbed UK, its role could be expanded to administration of interoperable simulation facilities as the 'front door' to customers seeking such services. With Zenzic managing contractual arrangements with individual simulation providers, this would have the advantage of being a single point of contact for customers. It would also build on Zenzic's existing reputation and outreach achieved through its activities to date. However, this shift of Zenzic's remit to encompass managing simulation projects could be a significant distraction from their broader CAM responsibilities. Funding of Zenzic's role through any additional charges levied on projects might also be resisted by simulation providers.

New organisation

An alternative approach would be for a new organisation to be created and funded by Government and/or contributions by CAM Testbed UK members. This would act as the 'front door' to simulation services across CAM Testbed UK, helping potential customers to understand what facilities are available and how they can be coordinated to meet the specific customer need. As with a Zenzic lead, this organisation would take responsibility for the initial customer interface, sales process and managing contracts. The role the organisation plays would be similar to that provided by the DSC.

Testbeds lead

Although the two previous approaches simplify engagement for the customer by offering a single 'front door' to the interoperable simulation facilities of CAM Testbed UK, a disadvantage is that it places greater distance in the relationship between the customer and the organisations delivering the simulation services and adds a layer of administration to the process. An alternative would be for the facilities within CAM Testbed UK to cooperate in the sales process and delivery of simulation projects with high level coordinating oversight from Zenzic – in a similar vein as is achieved with physical CAM testing and trialling. To achieve a smooth customer experience, the facilities within CAM Testbed UK would need to have established processes for collaborating on simulation project delivery so that contracts and intellectual property issues can be dealt with quickly and easily.

12 | Opportunities for interoperable simulation in CAM Testbed UK

12.1 Expanding CAV safety testing

The most frequently referenced use for interoperable simulation was to enable developers to extend the scale and scope of their CAV safety testing. Having access to a broad range of interoperable simulation testing facilities would mean that a developer that had only tested their CAV in a narrow design domain (whether in simulation, on test tracks or in the real world) could examine the performance of their CAV in a wider set of environments. For example, a developer that had tested their CAV in temperate weather could extend their evaluation to other climatic conditions to increase the confidence that the vehicle was capable of operating in a wider operational design domain (thereby expanding the conditions and markets for which the CAV would be suitable). Alternatively, a developer that had successfully trialled their vehicle with an articulated pedestrian dummy on a test track could examine how their CAV would behave in a simulated complex urban environment with multiple pedestrians and other traffic. In short, a range of accessible and interoperable simulation facilities operating across CAM Testbed UK has the potential to enable CAV developers to extend their confidence in the performance envelope of their vehicles and accelerate their route to market.

In the stakeholder engagement process, a vehicle manufacturer felt that controlled environment and public road trials were more useful for CAV R&D than simulation at present, indicating that real world approaches offer a better mix of flexibility and control over the trial environment as well as providing direct evidence of system performance in a live environment. If interoperable simulation were to offer greater variety and flexibility of simulated test scenarios than traditional simulation approaches with a high degree of confidence over the validity of the simulation models and an ability to link simulation trials to real world testing activities, it may help to convince CAV developers to migrate (some) real-world testing activities to simulation. It was also recognised that lower tier suppliers to vehicle manufacturers who may not have the resources or capabilities to build a full CAV vehicle may value simulation tools in order to develop their products before pitching to a manufacturer.

12.2 Scenario library testing

CAM Testbed UK will have access to a library of standardised scenarios for CAV testing. Interoperability of simulation could enable multiple developers to test their automated driving systems on these standardised scenarios to understand how their technology compares to industry best practice and identify the scenarios in which their systems require further development to achieve an acceptable performance level. A customer seeking scenarios specifically related to associated real world testing at a physical testbed can work with that testbed facility on optimising a combined simulation and real-world testing programme based on the extended functionality that is enabled by interoperability of simulation across CAM Testbed UK.

12.3 Cost effective testing

As reported in Kalra and Paddock (2016), a CAV may require billions of miles of testing in the real world before it could be demonstrated as being statistically safer than a human driven car. This estimation depends on drivers naturalistically encountering scenarios of interest and observing how they behave to minimise risk and avoid incidents. Consequently, a large proportion of those miles are essentially uninteresting, filling the gaps between the next scenario of interest. Simulation allows testing organisations to focus on these scenarios of interest, thereby dramatically increasing the efficiency of testing. This approach has two key caveats – firstly, that all scenarios of interest (or a sufficiently representative sample thereof) within the CAV's intended operational design domain can be identified and characterised successfully in the simulation and secondly, that the simulation has sufficient fidelity and validity to deliver representative results of CAV behaviour in the critical scenarios. Interoperable simulation raises the prospect of meeting these criteria by enabling testing to cover a wider range of scenarios than might be achieved using an individual facility and, by connecting proven high fidelity simulation facilities through interoperability, a customer can have confidence in the results.

The described approach refers to the behaviour of a complete CAV but similar principles apply across the spectrum of CAM testing and development, from subsystems up to operation and business models at city or regional scale. Provided the required simulation fidelity and validity is achieved, simulation can dramatically improve the practicality, time efficiency and cost effectiveness of CAM testing. Interoperability allows facilities across CAM Testbed UK to optimise simulations by exploiting the best software and hardware resources, thereby increasing the chances that fidelity and validity are achieved and that customer requirements can be met.

12.4 Multi-domain testing

A key benefit of CAM Testbed UK is that it offers a mix of virtual and physical test environments covering a wide range of CAV operational design domains. Interoperability of simulation means that a customer undertaking simulations of CAV systems with a facility focused on urban environments can more readily translate that testing into the real world at a physical test track at another CAM Testbed UK facility through the sharing of simulation assets and coordination of testing approaches. This ability to transition easily between virtual, test track and real-world testing across multiple CAM Testbed UK facilities was recognised as being valuable by stakeholders.

12.5 Regulatory testing

The respective processes by which CAVs are approved for public road testing and commercial deployment are evolving. A widely held belief across stakeholders engaged in this review is that simulation will play a role in how a manufacturer demonstrates that a CAV displays an acceptable level of performance as one element of a required approvals process before progressing to on-road operations. As an example, one stakeholder referenced EuroNCAP's plans to develop virtual testing approaches for assisted and automated driving functions. By combining simulation capabilities across the member organisations, CAM Testbed UK should position itself to offer such regulatory simulation testing. Furthermore, member organisations of CAM Testbed UK should be able to offer consultancy services to support customer organisations in developing their products to pass these tests.

12.6 Interoperability beyond CAM Testbed UK

The PoC study in Stream 1 confirmed that interoperability can be achieved between organisations within CAM Testbed UK. However, as illustrated in Figure 11.1, successfully applying protocols for interoperability of simulation facilities *within* CAM Testbed UK opens the potential for using those protocols with organisations *beyond* CAM Testbed UK. Multiple organisations within CAM Testbed UK could work with one (or more) customers/collaborators on CAV testing, trialling and development. A single customer organisation could work with multiple CAM Testbed UK facilities. This dramatically increases the potential customer base for CAM Testbed UK and opens the door for organisations from outside CAM Testbed UK to collaborate in offering additional services to the market – further extending the market for which interoperable simulation services are relevant.

13 | Conclusion and recommendations

13.1 Operating model

The emerging recommendation of operation of interoperable simulation facilities for CAM Testbed UK is that activity is led by testbeds and coordinated through the existing Zenzic community structure. Customers will need to be able to access an up-to-date list of simulation assets and interoperability competencies (each with key contact points at each testbed facility). The Convex data exchange facility may be able to offer this service. The CAM Testbed UK facilities should build on existing relationships and working practices for multisite testing to establish the model by which interoperable simulation is delivered to the market. Emerging best practices for doing this should be shared with other CAM Testbed UK facilities through the existing community activities. Investment may be needed to develop and align specific simulation interoperability working protocols across CAM Testbed UK and to create marketing materials and sales activities to raise awareness of the interoperable simulation capabilities. Importantly, CAM Testbed UK interoperable simulation services must provide a seamless straightforward and consistent customer journey where organisations can have complete confidence that their IP is being adequately protected/secured and where collaboration with other CAM Testbed UK partners in an interoperable simulation proposition generates no undue technical, financial or administrative friction in project delivery.

13.2 Systems and services

Experience in Stream 1 of the interoperable simulation project confirmed that, although its use comes with a small cost, a middleware data distribution service (DDS) platform was helpful in managing the timely and secure distribution of data across multiple systems participating in the interoperable simulation. The DDS also facilitates the process of engaging other simulations and customers into collaborative activities by reducing the technical challenge in connecting systems together and adding layers of protection to data exchanges. Several organisations, platforms and technologies were identified as being commonly used in CAV simulation and therefore efforts should be made to ensure simulation services across CAM Testbed UK are compatible with such systems (listed in Section 11.3 Compatibility).

Unlike the physical testbeds that constitute CAM Testbed UK, interoperable simulation facilities do not necessarily gain from being close geographically. This opens the potential for other national (and international) facilities to play a role in the interoperable simulation platform – for example:

- A German CAV developer uses vehicle dynamics simulations from a local supplier but wants to expand the scope of their testing by using traffic simulation and urban environment simulation facilities available through CAM Testbed UK.

- A UK CAV developer wants to explore how their platform would perform on U.S. road environments so connects their existing interoperable simulation systems to a simulated road environment from a U.S. partner.
- A Japanese vehicle manufacturer wants to expand the scope of their CAM Testbed UK proving ground tests of CAV to look at human-machine interface issues by using a motion-based simulator and so connects their CAV dynamics model to a high-fidelity driving simulator in the UK.

Simulation services should be offered in five different channels:

- Simulation of CAV subsystems
- Simulation of CAV behaviour
- Simulation of CAV-human interaction
- Simulation of CAV HiL
- Simulation of CAV system level effects

For each channel, clarity is needed over the level of simulation fidelity required in order to fulfil customer requirements. Simulation service providers need to carefully interpret results based on the known veracity and validity of the complete interoperating simulation and its constituent components.

13.3 Market offer

Although the recommended operating model suggests leadership of CAM Testbed UK simulation services should be distributed across the ecosystem, the market offer should still be easy to discover and navigate with clear descriptions of how interoperability of simulation facilities enable efficient CAM research and development, closely linked to real world testing facilities. The offering should be refined enough so that large organisations can understand how the simulation services offered enable cost effective acceleration of CAM development, with pathways illustrating how simulation progresses to real world testing in the CAM Testbed UK facilities. It should be easily accessible from international locations; for example, it should be as easy for a company in the U.S. to engage with CAM Testbed UK simulation technologies as if the facilities were located in their country. The CAM Testbed UK interoperable simulation services should also be accessible to research organisations and start-ups so that they can progress their CAM programmes effectively and efficiently through use of the simulation facilities available across CAM Testbed UK, thereby supporting the CAM ecosystem in the UK and beyond.

13.4 Recommended actions and business plan

Establishing a CAM Testbed UK interoperable simulation community

In addition to Zenzic's activities in the strategic coordination of CAM Testbed UK, a community dedicated to interoperable simulation should be established to build on the PoC (Stream 1) and the recommendations of this report (Stream 2). This should have an independent chair with industry experience, be attended by key simulation leads from the facilities and supported by strategic advisors from across the industry. The purpose of the community would be to:

- develop (and track progress against) a strategic plan for interoperable simulation within CAM Testbed UK;
- ensure coordination of simulation activities and protocols across CAM Testbed UK;
- for collaborative opportunities, identify target customers and services to be developed;
- share relevant information on market engagement and forthcoming opportunities;
- provide simulation system status updates and identify individual/community upgrade paths;
- share any (foreseen or unforeseen) technical challenges (at a strategic level);
- align and prioritise future investments in interoperable simulation services;
- report status to Zenzic and coordinate strategic approach.

This list is almost a starting template for an agenda for meetings of the CAM Testbed UK interoperable simulation community.

Note that whilst facility members of the interoperable simulation community would initially comprise organisations from within CAM Testbed UK, there is significant potential in allowing membership to expand with other simulation facilities within the UK and beyond being able to join and contribute. This would be subject to their agreement to a defined set of operating principles and fulfilling required technical criteria for interoperability with CAM Testbed UK's simulation facilities. However, there is the potential for this community to become highly influential in the use of simulation for CAM testing and development.

Marketing of CAM Testbed UK interoperable simulation capabilities

A 'front door' organisation would make marketing of interoperable simulation capabilities more straightforward. However, due to the additional complexity and administrative overhead of this approach, the recommended operating model is for each testbed to lead market engagement on simulation on behalf of their own facility. This distributed approach makes marketing more challenging but:

- market engagement is coordinated under a consistent brand 'look and feel';
- opportunities are shared with other organisations within CAM Testbed UK where relevant;
- CAM Testbed UK customers are made aware of simulation capabilities at other sites within CAM Testbed UK;
- interoperable simulation opportunities and business development priorities are shared and aligned through the CAM Testbed UK interoperable simulation community.

It was recognised that customers would need to be able to access a convenient and up-to-date catalogue of all the simulation capabilities across CAM Testbed UK. This should contain sufficient technical detail to help organisations determine whether the simulation facilities meet their requirements and understand how they can engage with the interoperable simulation capabilities. It should also contain key contact information to allow potential customers to follow up with suitably knowledgeable simulation leads at each facility. The Convex data exchange facility was identified as a potential platform for hosting this information. Use of Convex in this way may symbiotically drive Convex customers towards the simulation facilities and drive simulation customers towards Convex.

Proof of concept: integration of additional simulation facilities

The Stream 1 PoC demonstrated that interoperable simulation between CAM Testbed UK facilities is practical and achievable and has laid foundations for further development. Two suggested extensions are proposed to enhance the capabilities of CAM Testbed UK interoperable simulation still further. The first would be to undertake a trial in which an academic institution outside of CAM Testbed UK uses their simulator facilities to participate in an interoperable simulation demonstration involving one or more facilities from within CAM Testbed UK. The second would be for a CAM developer organisation/vehicle manufacturer to run their existing simulation systems through the CAM Testbed UK interoperability platform, again working with one or more facilities from within CAM Testbed UK. In addition to helping the CAM Testbed UK facilities to identify and resolve any issues in the interoperable simulation platform, these PoCs would also push CAM Testbed UK further towards the diagram shown Figure 11.1(D), where multiple organisations from within CAM Testbed UK can work seamlessly with multiple collaborator / customer organisations from outside of CAM Testbed UK and create the conditions for future commercial projects. Furthermore, success with these demonstrations would provide significant marketing collateral for engagement with potential customers.

Investment required

Discussions with the team delivering the Stream 1 PoC estimated that to achieve the technical components of these recommendations would require an estimated investment of £500k over two years. With additional support to deliver the non-technical recommendations, the progress that could be achieved relative to the $10m investment being made in the VOICES project over a similar two-year timeframe appears to represent significant value for money. The key question is whether that value for money delivers a return on investment. With interoperable simulation being relatively immature for CAM development and with customer organisations unwilling to commit firmly to figures on how much they would spend on interoperable simulation for CAM testing and development, it is difficult to estimate a revenue figure for interoperable simulation services across CAM Testbed UK. However, it was unanimously agreed that simulation is likely to play a critical role in CAM development, evaluation and certification and so being able to offer a greater variety of simulation capabilities through interoperability is prudent and, even if there is not an instant financial return, the skills gained by organisations and individual engineers across the CAM Testbed UK community in enabling such services would be highly prized. Using interoperability to deliver greater sophistication and depth of simulations whilst creating a potentially valuable niche for CAM Testbed UK appears to be a worthwhile avenue to pursue.

13.5 Conclusion

For several years, it has seemed that CAM was imminent and would soon be a common sight on the roads of cities and towns around the world. Whilst the anticipated benefits of CAM remain, such as improved safety, greater accessibility of transport and freedom from time spent driving, making this vision a reality has proved harder than had been anticipated. Progress is undoubtedly being made but the requirement to prove safe operation of CAM in the infinite variety of public road environments is proving a tough hurdle to overcome. Simulation is a tool that offers developers routes to attack this problem by cost-effectively providing greater speed and flexibility of approach. This must be tempered against the critical need for simulation facilities to achieve the required level of fidelity and validity to generate useful and practical outcomes for their users. Interoperability raises the complexity of simulation by enabling separate systems to interact. However, these interactions open new possibilities for CAM testing and development that may help us to tackle these challenges. Particular opportunities were identified in extending the envelope of CAV safety testing, standardised evaluations across a library of test scenarios, improving the cost effectiveness of CAM development, easing the path between virtual and physical tests and opening the possibilities for interoperability with customers and/or collaborators beyond CAM Testbed UK.

The Stream 1 PoC demonstrated that interoperability across CAM Testbed UK simulation facilities is achievable and can deliver valuable outcomes for a CAV developer. However, while the PoC is a great technical achievement, it achieves little in isolation. This review and stakeholder engagement report has identified that simulation is likely to play a key role in the development, evaluation and certification of CAVs and that interoperability may help to accelerate progress of CAVs through the engineering V-model by offering test and development environments with the required sophistication, depth, fidelity and validity and that may smooth the path between virtual and physical testing. However, there is much work to do to make interoperable simulation across CAM Testbed UK a success.

Recommendations identified that the testbed facilities should collaborate in driving interoperable simulation, rather than be coordinated by a dedicated 'front door' organisation, but their activities should be guided and coordinated by a strategic interoperable simulation community group. This group would set out the strategic plan for interoperable simulation within CAM Testbed UK and ensure cooperation and alignment between its member facilities. The marketing approach needs to attract customers with clear and coherent messaging about what interoperable simulation can achieve and how CAM Testbed UK facilities can collaborate seamlessly in its delivery. Additional PoC demonstrators would extend the interoperable simulation capabilities of CAM Testbed UK and help to generate interest in the approach. These recommendations cannot be completed without additional investment but the market for interoperable simulation is untested. However, with international competitors ramping up activity and an undoubted need for detailed simulations in the development, evaluation and certification of CAVs, there is every likelihood that such an investment would generate a positive return.

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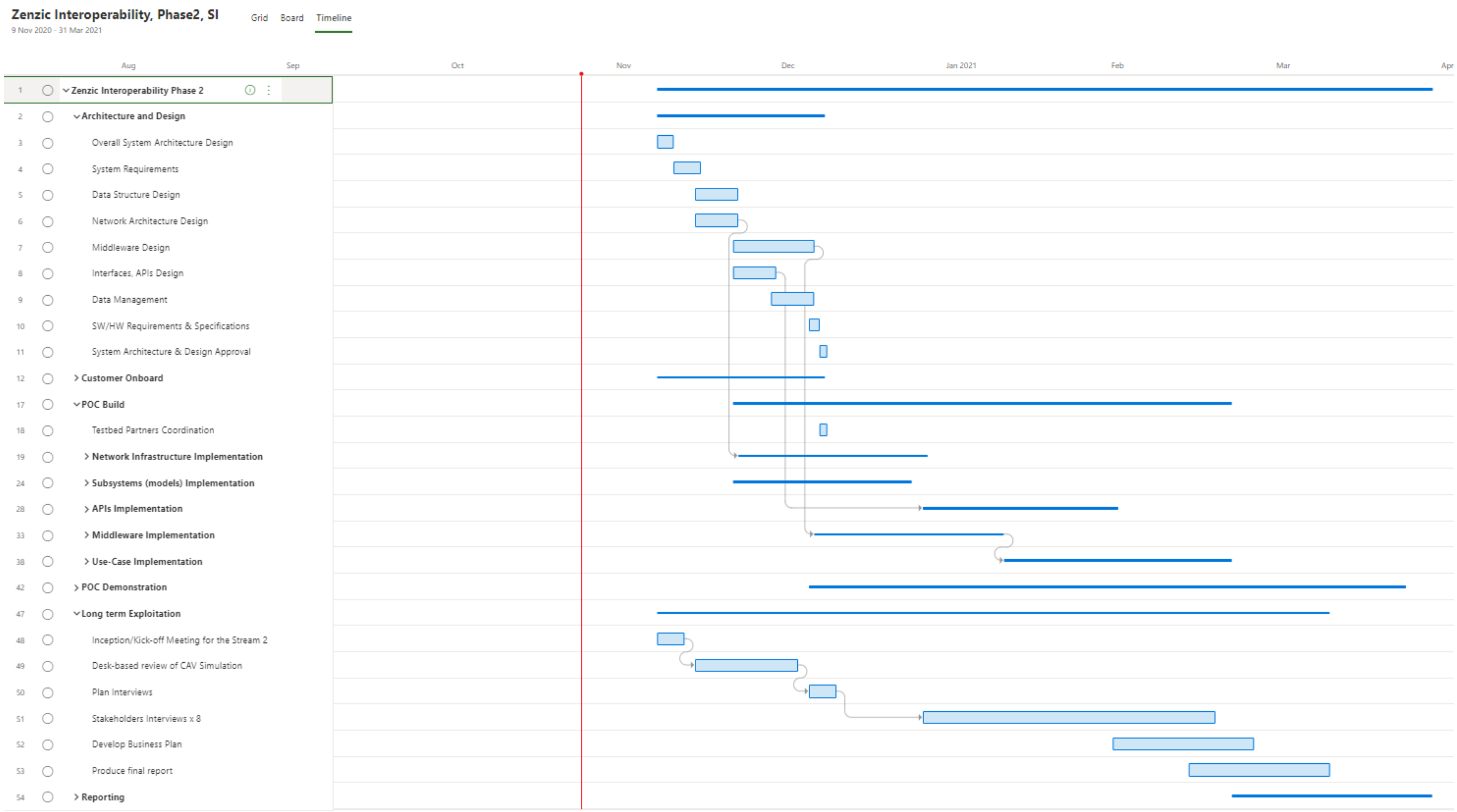
Appendices

Appendix A. Project Gantt Chart



Appendix B. Project scenarios

A1: Pedestrian Crossing at Armstrong Road

Description:

- Pedestrian crosses the road suddenly from the right at undesignated crossing area.
- Ego vehicle continuing straight at 5 mph.

SDL:

INITIAL: Ego [V0] in [R1.L1] at [20.0] map location AND Pedestrian [P1] in [R1.L3] at [40.0] map position

WHEN: Ego [V0] is [Going ahead]

DO: Pedestrian [P1] manoeuvre as:

Phase 1: [P1] WalkForward_MovT [-, 1 to 4, 0 to 1] [V0: FSL]

Phase 2: [P1] WalkForward_Cross [-, 2 to 5, -1 to 1] [V0: F]

Phase 3: [P1] WalkForward_MovA [-, 1 to 4, -2 to 0] [V0: FSR]

END: [P1] relative location to [V0] is [not within] a [longitudinal] margin of [5.0]

A2: Traffic vehicle turn right with cut in

Description:

- Traffic vehicle enters junction and turns right to cut in in front of the ego vehicle.
- Ego vehicle continuing straight at 5 mph.

SDL:

INITIAL: Ego [EGO] is [Going ahead] in [R3.L1] at [20.0] map location AND On-Road Vehicle [V1] in [S2.L2] at [10.0] map position

WHEN: Ego [EGO] is [Going ahead]

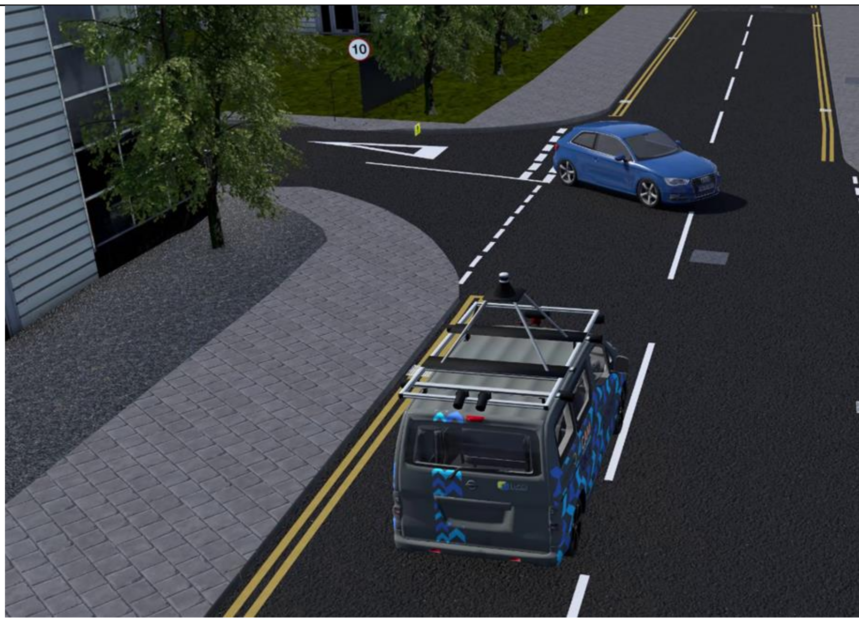
DO: On-Road Vehicle [V1] manoeuvre as:

Phase 1: [V1] Drive_Towards [-, 25 to 35, 2 to 3] [V0: -5 to 5, FSR]

Phase 2: [V1] TurnRight_CutIn [J2, 30 to 40, 2 to 3] [V0: 0 to 5, FSR]

Phase 3: [V1] Drive_Away [-, 35 to 45, 0 to 1] [V0: 5 to 15, F]

END: [V1] relative location to [V0] is [not within] a [longitudinal] margin of [10.0]



A3: Pedestrian crossing behind car at Cadogan Road

Description:

- Pedestrian crosses the road. Traffic vehicle stopped at opposite side of the road blocking line of sight of ego vehicle.
- Ego vehicle continuing straight at 5 mph.

SDL:

INITIAL: Ego [V0] in [R9.L1] at [55.0] map position AND On-Road Vehicle [V2] in [R9.L2] at [60.0] map position AND Pedestrian [P2] in [R9.L4] at [65.0] map position

WHEN: Ego [V0] is [Going ahead]

DO: Pedestrian [P2] manoeuvre as:

Phase 1: [P2] WalkForward_MovT [-, 1 to 4, 0 to 1] [V0: FSR]

Phase 2: [P2] WalkForward_Cross [-, 2 to 5, -1 to 1] [V0: F]

Phase 3: [P2] WalkForward_MovA [-, 1 to 4, -2 to 0] [V0: FSL]

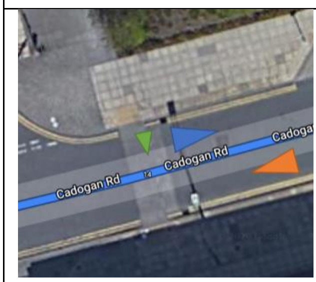
AND On-road vehicle [V2] manoeuvre as:

Phase 1: [V2] Stopped [-, 0 to 0, 0 to 0] [V0: FSR]

Phase 2: [V2] Stopped [-, 0 to 0, 0 to 0] [V0: SR]

Phase 3: [V2] Stopped [-, 0 to 0, 0 to 0] [V0: RSR]

END: [P2] relative location to [V0] is [not within] a [longitudinal] margin of [10.0]



A4: Pedestrian running across the road behind road vehicle at Carriage Street

Description:

- Pedestrian crosses the road while traffic vehicle heading in opposite direction. GPS signal loss occurs.
- Ego vehicle continuing straight at 5 mph.

SDL:

INITIAL: Ego [EGO] in [R15.L1] at [5.0] map position AND On-Road Vehicle [V4] in [R15.L2] at [15.0] map position AND Pedestrian [P3] in [R16.L3] at [3.0] map position

WHEN: Ego [EGO] is [Going ahead]

DO: Pedestrian [P3] manoeuvre as:

Phase 1: [P3] WalkForward_MovT [-, 1 to 4, 0 to 1] [V0: FSL]

Phase 2: [P3] WalkForward_Cross [-, 2 to 5, -1 to 1] [V0: F]

Phase 3: [P3] WalkForward_MovA [-, 1 to 4, -2 to 0] [V0: FSR]

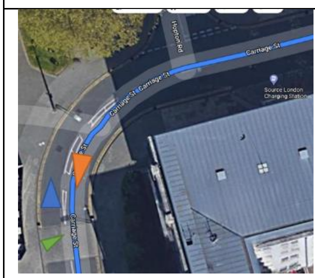
AND On-road vehicle [V4] manoeuvre as:

Phase 1: [V4] Stopped [-, 0 to 0, 0 to 0] [V0: FSR]

Phase 2: [V4] Stopped [-, 0 to 0, 0 to 0] [V0: SR]

Phase 3: [V4] Stopped [-, 0 to 0, 0 to 0] [V0: RSR]

END: [P3] relative location to [V0] is [not within] a [longitudinal] margin of [15.0]



A5: Pedestrian crossing the road behind HGV obstructing FOV at Carriage Street

Description:

- Pedestrian runs across the road behind large vehicle.
- Ego vehicle continuing straight at 5 mph.
- View obstructed by large vehicle.

SDL:

INITIAL: On-Road Vehicle [V5] in [R16.L2] at [55.0] map position AND Pedestrian [P4] in [R16.L4] at [62.0] map position

WHEN: Ego [EGO] is [Goingahead] in [R16.L1] at map location [59.0]

DO: Pedestrian [P4] manoeuvre as:

Phase 1: [P4] WalkForward_MovT [-, 1 to 4, 0 to 1] [V0: FSR]

Phase 2: [P4] WalkForward_Cross [-, 2 to 5, -1 to 1] [V0: F]

Phase 3: [P4] WalkForward_MovA [-, 1 to 4, -2 to 0] [V0: FSL]

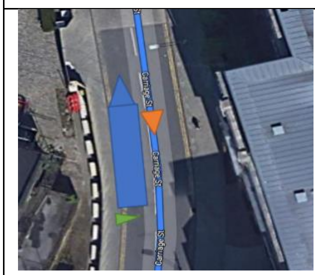
AND On-road vehicle [V5] manoeuvre as:

Phase 1: [V5] Stopped [-, 0 to 0, 0 to 0] [V0: FSR]

Phase 2: [V5] Stopped [-, 0 to 0, 0 to 0] [V0: SR]

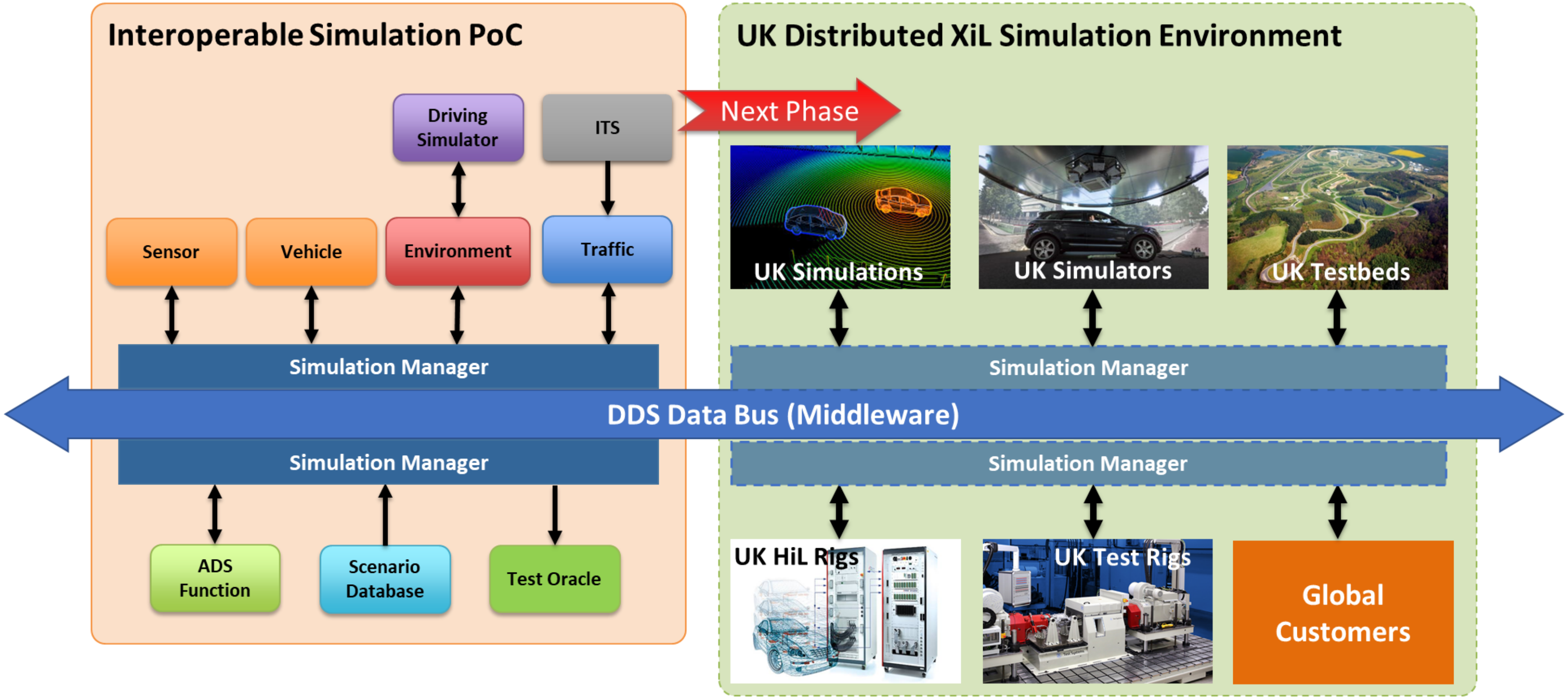
Phase 3: [V5] Stopped [-, 0 to 0, 0 to 0] [V0: RSR]

END: [P4] relative location to [V0] is [not within] a [longitudinal] margin of [15.0]



Appendix C. Project outlook

A Fully Integrated / Distributed Simulation & Real-world Environment



Source: Author Created

Appendix D. Stakeholder engagement

Representatives from eight organisations were interviewed to gauge their responses to the proposed interoperable simulation approach for CAM Testbed UK. Meetings were all held in Quarter 1 of 2021, each lasting around 60 minutes and based around a set of semi-structured questions – varying slightly depending on the domain knowledge of the participant. Discussions were held under the Chatham House rule – no content of the report is attributed to any individuals or organisations. The roles and organisations represented in the interviews are listed in Table 1.

Table 1. Roles and organisations represented in the stakeholder interview process

Role	Organisation
Front Door Manager	Defence Simulation Centre
Principal Technologist	Connected Places Catapult
Chair in Driving Simulation	University of Leeds
Director of Research	Thatcham Research
Operations Director	rFpro
Head of Automated Vehicle Technologies	Department for Transport
Senior Engineer	Nissan
Chief Strategy Office / Founder	Roborace / ADA
Strategic and Business Development	ZF Group

Appendix E. Simulation facilities across CAM Testbed UK

In a review of simulation facilities available across the CAM Testbed UK environments, 129 simulation types were identified as being offered for CAV testing and development. These split across six simulation types and ten categories:

Simulation types:

- Offline Simulation (Model-in-the-Loop)
- Realtime Simulation (Software-in-the-Loop)
- XiL Simulation ("Something"-in-the-Loop)
- Mixed Reality Simulation (VR/AR)
- Connected Reality Simulation (integrated real-world testing and simulation, using connectivity)
- Soft realtime / offline simulation

Simulation capabilities:

- Actuator (e.g. powertrain, accelerator / brake / steering etc.)
- Communication (e.g. WiFi, 5G, DSRC, C-V2X etc.)
- Control / Decision / Localisation / Perception systems (e.g. ADAS, ADS)
- Data management
- Driver (e.g. human-in-loop driving simulators, virtual driving models, VR/AR environments)
- Environment / Road (e.g. models of test environments, vehicle models etc.)
- Scenario management (creation of test scenarios using available features)
- Sensor (e.g. simulation of camera, radar, lidar sensors etc.)
- Traffic (e.g. VISSIM, SUMO, CARLA etc.)
- Vehicle (various models of vehicle type and behaviour)

The simulation capabilities represent a diverse mix of hardware and software types (in-house, licensed, open source etc.), raising the complexity in making them interoperable.

In addition, 110 data sources on the Convex platform were identified as having relevance to CAV simulation testing.

Appendix F. Case study: Defence Simulation Centre

The Defence Simulation Centre (DSC) provides a focal point for all modelling and simulation across defence, directly supporting the Defence Modelling and Simulation Coherence (DMaSC) approach. Based in Shrivenham, it is part of the Defence Academy of the United Kingdom and holds simulation assets including 3D models, terrain data and software tools. The DSC works to promote interoperability across simulation activities for the British Army, Royal Navy and Royal Air Force, each of which has staff serving as Service Command Technical Authorities – their role is to:

- guide use of simulation in an interoperable manner;
- ensure that simulation programmes follow relevant standards (JSP939 – MoD Defence policy for modelling and simulation – see Appendix G).

Guidance from the DSC seeks to deliver military simulations that are not locked into proprietary standards or formats unless there are compelling reasons to do so (e.g. secrecy). DSC is supported by a network of SMEs that can offer technical assistance to customers and simulation facilities as needed.

Models used by the DSC apply the SISO (Simulation Interoperability Standards Organisation) enumerations, as used across NATO, to facilitate compatibility and interoperability.

Interoperable simulations use a specific MoD fibre-optic network. This helps to ensure reliability and cybersecurity is managed to a high degree. Simulation assets used by the DSC are MoD IP; this can be costly but suppliers understand the rules and this IP ownership facilitates re-use of assets in other simulation exercises.

Coordination of military simulation by the DSC offers helpful insights into how the operation, coordination and interoperability of simulation facilities can be achieved. By comparison to CAM Testbed UK, the coordination of simulation in the military has two key advantages:

- **Consistent customer** – military simulations will tend to be delivered in support of national defence activities. This customer can demand that interoperability is baked into simulation to support longer term efficiency.
- **Command hierarchy** – interoperability is recognised as a critical feature of military simulation and this is enforced through the chain of command and clear, standardised approaches (JSP939).

In seeking to serve a variety of customers with no formal hierarchy in place to mandate coordination of systems and protocols, ensuring ongoing interoperability is more challenging for CAM Testbed UK.

Appendix G. JSP939 Defence Policy for Modelling & Simulation (M&S)

JSP939 is the reference framework document aimed at coordinating activity, guidance and acquisition of modelling and simulation activities to enable Defence achieve the maximum return on investment. As such it offers useful guidance on how interoperable simulation might emerge across CAM Testbed UK.

JSP939 is structured in two parts: Part 1 describes the direction that must be followed in accordance with statute or policy mandated by Defence, or on Defence by Central Government; Part 2 provides the guidance and best practice that will assist the user to complying with Part 1.

The key principles specified in JSP939 Part 1 are:

- Defence modelling and simulation resources and knowledge are to be developed and exploited through the DSC (Defence Simulation Centre).
- Modelling and simulation is to be developed to deliver the widest possible benefits and maximise value for money.
- Changes to modelling and simulation activities are to be coordinated through DSC.
- Interoperability is to be considered for all modelling and simulation systems and developed through a common technical architectural approach and the reuse of data.

A series of rules then defines how organisations undertaking modelling and simulation should achieve compliance, highlighting the importance of:

- reuse of existing assets;
- procuring in ways that maximise opportunities for reuse;
- using standardised processes and architectures;
- documenting activities;
- sourcing and sharing assets through / with the DSC, including research outputs.

JSP939 Part 2 highlights how JSP939 applies for all Defence projects and describes the Defence Modelling and Simulation Coherence (DMaSC) operating model, which illustrates how modelling and simulation activities are governed across the Defence sector.

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