CAT4Yards D1.1

Status of CAT in public and private areas

Report of literature study and interviews

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CAT4Yards D1.1

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Management Summary
Work Package 1 (WP1) of the CAT4Yards project aimed to establish a clear and up-to-date State of the Art (SoTA) overview of Connected and Automated Transport (CAT) and the conditions required for its successful implementation in logistics environments.
This knowledge base forms the foundation for the Impact Assessment Tool being developed in WP2, which will quantify the effects of CAT deployment in three use cases (DPD (WP3), Elopak-Verbrugge (WP4) and QTerminals Kramer (WP5).

To achieve this, WP1 combined two complementary research approaches: extensive desk research into technological, organisational, legal, and human-factor developments, and interviews with experts and stakeholders from ongoing CAT pilot and deployment projects. Findings were analysed across four CAT integration building blocks: **Vehicle & Control, Logistics & People, Organisation, and Laws & Regulations.**

Key findings from the desk research
The desk research shows that CAT is not a standalone technical innovation, but a system-level transformation requiring alignment between vehicles, infrastructure, control systems, workforce roles, governance, and regulation.

- **Vehicle & Control:**
  Automation levels, control tower capabilities, and digital/physical infrastructure are tightly interdependent. Advanced autonomous vehicles require reliable 5G/6G connectivity, geofenced yard layouts, charging systems, and integration with TOS/YMS. Current limitations include operator scalability, video latency for teleoperation, and lack of standardised interfaces.
- **Logistics & People:**
  CAT alters traffic management and reshapes workforce tasks. Fully automated operations rely on centralised orchestration platforms, while mixed-traffic environments require careful coordination between human-driven and automated vehicles. Automation shifts human roles from driving to supervision and exception handling, highlighting new skill requirements.
- **Organisation:**
  Governance structures are often unclear. Responsibilities for infrastructure investment, system monitoring, safety oversight, and workforce training are distributed across site owners, technology providers, and regulators. The absence of consistent governance frameworks is a barrier to scalable deployment.
- **Laws & Regulations:**
  Legal conditions heavily influence what is possible. Private industrial sites allow more flexibility under workplace and machinery law, whereas public road operations remain constrained by national traffic legislation that still requires a legally responsible driver. Uncertainties around liability, certification, and data management remain significant challenges.

Insights from stakeholder interviews
Interviews with project stakeholders confirmed many SoTA observations and revealed three cross-cutting themes:

- **Digitisation as a prerequisite for automation:**
  Well-structured and digitised yard processes, supported by a robust Yard Management System, greatly simplify CAT integration. Even without automation, digitisation alone brings measurable benefits.
- **Urgent need for standardisation:**
  Stakeholders emphasise the lack of standardised processes, communication protocols, and physical infrastructure. Standardisation is crucial for interoperability, vendor-agnostic integration, and scaling CAT between sites.
- **The critical role of the human factor:**
  Despite automation reducing the need for driving personnel, human involvement remains essential for supervision, exception handling, safe operation, and organisational acceptance. Clear communication and training are necessary to maintain safety and avoid resistance from workers or society.

Overall synthesis and implications for WP2
The combined analysis shows that CAT readiness cannot be evaluated purely on the maturity of vehicle technology. Successful deployment depends on coherence across all four building blocks:

- Vehicle & Control provides technological capability;
- Logistics & People ensure safe operational integration;
- Organisation determines governance and accountability;
- Laws & Regulations define the legal boundary conditions.

For WP2, this means that the Impact Assessment Tool must treat building-block parameters as interconnected, not isolated. Choices such as autonomy level, fleet size, or vehicle type inherently influence requirements for connectivity, control tower staffing, training, safety governance, and legal compliance.

WP1 therefore delivers insights needed for realistic CAT scenario modelling in WP2 and supports the broader CAT4Yards objective of enabling safe, scalable, and economically viable automated transport operations.

1 Introduction

Connected and Automated Transport (CAT) for heavy road transport is widely expected to deliver significant business, environmental, and societal benefits in the coming years. Among potential application areas, logistics yards stand out as the most promising short-term environment for deploying automated vehicles, offering strong prospects for viable business cases. For logistics companies, CAT implementation on yards can enhance efficiency, safety, and sustainability. At the same time, automotive manufacturers see yards as an ideal testing ground for the first real-world applications of automated vehicles and related digital infrastructure. However, experiences from the CATALYST Living Lab have revealed a fundamental "chicken-and-egg" problem that hinders progress [1]. Logistics companies are interested in experimenting with CAT but often lack insight into the specific efforts, requirements, and organisational changes needed at their site. Without this understanding, they struggle to formulate the right questions for automotive suppliers. Conversely, automotive parties have limited visibility into the operational needs and criteria of logistics processes, making it difficult to design solutions that fit seamlessly into yard operations. Bridging this gap is essential for enabling successful real-world CAT deployment.

The CAT4Yards project directly addresses this challenge by investigating the efforts, requirements, and impacts associated with implementing CAT in yard environments. The central research question guiding the project is: What efforts and requirements are needed regarding yard, vehicle, control, and people to implement CAT at yards, and what are the associated impacts?

To answer this question, the project follows a design research approach. **First, relevant knowledge and results from previous CAT initiatives are collected and analysed in Work Package 1 (WP1) and presented in this report**. This "state of the art" analysis forms the foundation for developing a general methodology and an impact assessment tool in Work Package 2 (WP2). Linking technological advancements in this field to their associated impacts involves multiple aspects, such as Vehicle & Control, Logistics & People, Organisation, Laws and Regulations surrounding CAT integration in any site. Figure 1 shows these building blocks and the impact indicators that the tool needs to predict for any given use case.

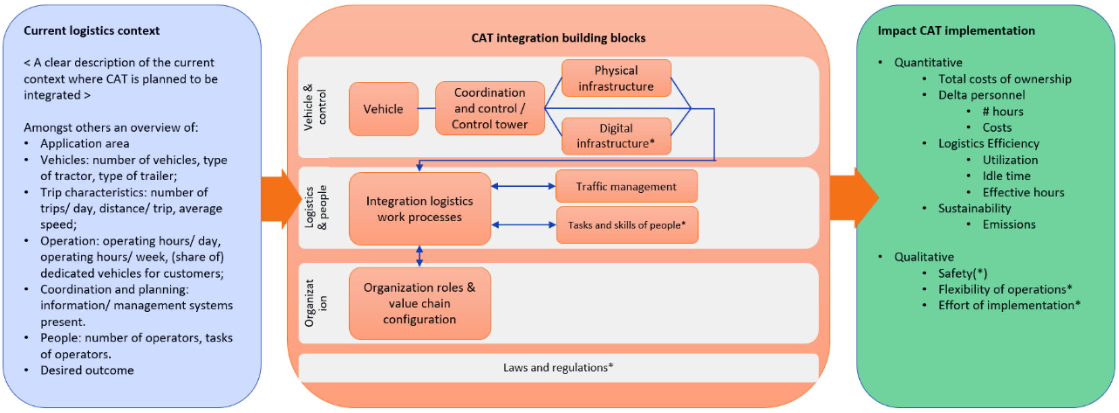

Figure 1: CAT building blocks [2].

The method and tool will then be applied and validated in three real-world use cases: the DPD distribution centre (WP3), the Elopak–Verbrugge yard and industrial area (WP4), and the QTerminals Kramer Rotterdam port area (WP5). Insights gained from these work packages will subsequently be used to explore additional conditions for applying CAT on short-distance public roads (WP6). Finally, dissemination and valorisation activities are covered in WP7, with project management embedded in WP8.

1.1 Goals of WP1

Within this context, the goals of Work Package 1 (WP1) are to provide input of current state-of-the-art (SoTA) of the CAT building blocks, that better inform the impact assessment tool of WP2 with up-to-date information. For example, current purchase prices of automated vehicles, infrastructure requirements for enabling certain automation level and their associated costs, etc. The knowledge gap in CAT implementation can thus be addressed and used in the WP2 Tool.

During the course of WP1, calibration sessions with WP2 led to certain focus areas that require attention for the parameters used in the tool:

- Current purchase prices of various types of CAT vehicles and estimates of future models;
- Operating costs of various types of CAT vehicles;
- Traffic management strategies and their interaction with digital infrastructure.

An additional goal of WP1 is to highlight bottlenecks, challenges and important insights related to CAT implementation from current and recently conducted pilot projects and commercial deployments. Hence, in parallel to desk research on the focus areas listed above, interviews are conducted with researchers and stakeholders working in various CAT projects. Desk research of CAT aspects together with interviews should help in filling the knowledge gaps where possible and provide insight to the WP2 Tool that could generate further knowledge to answer the highlighted questions.

Hence, a research methodology has been used that can capture the current state of technology, commercial and pilot implementation experience, and potential impact on various stakeholders.

1.2 Methodology

A bottom-up qualitative research approach is chosen to tackle the study of the SoTA, where data sources are gathered and analysed to identify required key indicators and draw conclusions. The building blocks shown in Figure 1 are used as a lens to categorize the findings. Figure 2 shows the developed methodology to get an overview of status of the building blocks and identify missing knowledge. This is done from two perspectives: SoTA study and Interviews with research pilot projects. The SoTA review considers scientific literature, commercial deployment reports, and pilot projects on CAT in both public and private domains, covering fully automated and mixed-traffic scenarios.

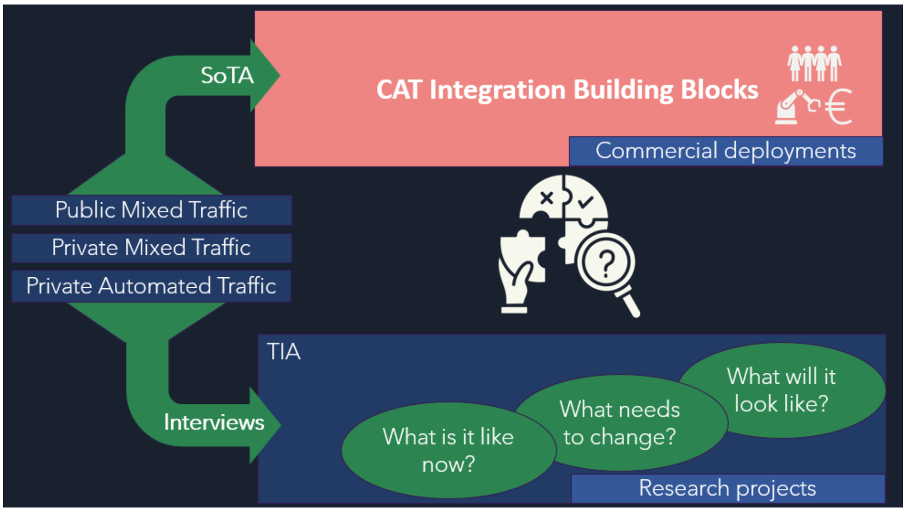

Figure 2: WP1 methodology for information gathering.

A Technology Impact Assessment (TIA) view is used in interviewing relevant CAT pilot projects. This is expected to result in challenges solved by the project and remaining bottlenecks to be solved. Simultaneously, the SoTA desk research on the CAT building blocks will give an overview of current technology and their associated costs and limitations. From this body of knowledge, the knowledge gaps are highlighted and conclusions are drawn to fill the gaps where possible, per building block. Unanswered questions are then made clear, for the WP2 Tool and further research to answer. Table 1 shows an example of how the conclusions can be made from the knowledge gathered on each building block from both perspectives.

Table 1: Example of bottom-up research approach

Building Block	Interview findings	SoTA findings	Conclusions
Vehicle	“Automation technology is advanced, but robust operation in adverse weather is remaining to be tackled.”	Data fusion techniques can mitigate weather effects, as proven in a certain study.	Manufacturers need to integrate available fusion techniques in their sensor stacks, but this has an impact on development and hardware cost.
Digital Infrastructure	“Network quality is severely affected by signal reflections in the metallic infrastructure of a port.”	Redundancy in localisation and communications hardware is essential to ensure consistent automated operation.	Site owners along with technology providers need to be aware of the relationship between physical and digital infrastructure.

The report goes through the current state of CAT, where specific building blocks are explored in detail. Commercial solutions and their current predicted costs, challenges identified by practical experience in deployments are explored per building block. Published sources are cited and links are provided for news articles where relevant. Then findings from interviews with researchers and stakeholders of CAT research projects are presented to gain an understanding of what problems are being solved and what are remaining challenges. Finally, the provided findings from both perspectives are analysed and conclusions are drawn.

2 Current State of CAT

This chapter presents the state-of-the-art (SoTA) of Connected and Automated Transport (CAT) using the three abstracted CAT4Yards building blocks: (1) Vehicle & Control, (2) Logistics & People, (3) Organisation, and (4) Laws and Regulations as shown in Figure 1. We integrate insights from recent pilots, academic publications and early commercial deployments and provide indicative costs where reliable sources exist. Where relevant, we distinguish between fully automated and mixed-traffic contexts, and between public-road and private-area (yards/ports/DCs) operations. Given the use cases of the CAT4Yards project, the laws and regulations surrounding CAT are investigated specifically for the Netherlands. The outcome in this chapter is to paint a picture of the state of technology readiness and highlight challenges faced in these building block areas. For each block, we highlight today's capabilities, typical deployment patterns and experience, and provide indicative cost ranges to support the modelling in WP2 and the conclusions in Chapter 4.

2.1 Vehicle & Control

The WP2 Tool uses certain vehicle archetypes that refer to various vehicle types.
The vehicle archetypes capable for public roads considered in CAT4Yards are listed below:

- Diesel truck;
- Electric truck;
- Autonomous diesel truck basic;
- Autonomous electric truck basic;
- Autonomous diesel truck advanced;
- Autonomous electric truck advanced.

Meanwhile in private area automation such as in yards or port environments, the following vehicle archetypes are considered:

- Electric trailer mover;
- Autonomous electric trailer mover;
- Diesel terminal tractor, Electric terminal tractor;
- Autonomous electric terminal tractor with cabin;
- Autonomous electric terminal tractor no cabin.

The following sub-sections discuss the deployments of such vehicles and their associated purchase costs. The physical and digital infrastructure that supports the use of the CAT vehicles are also studied, where the current challenges are highlighted.

2.1.1 Vehicles - public road

The autonomous trucking field is constantly evolving, with tech startups being started, acquired, partnering, and shutdown regularly. Commercial deployments are only recently being rolled out in specific partnerships and quite a few vehicles are being used in pilot programs, but there are no publicly advertised driverless trucks on sale.

European Union (EU) and United States (US) players continue pre-commercial operations (driver-in/driver-out), with commercialisation targets in the 2025–2027 window depending on corridor, safety case, and regulation. Table 2 shows the current state of notable deployments and pilot programs.

Table 2: A selected list of pilot programs related to autonomous trucks.

Autonomous Truck Name	Deployment status
Aurora Innovation (Paccar and Volvo models)	After many delays, Aurora became the first company to launch commercial driverless trucking operations on public roads in April 2025. The company operates on the Dallas-to-Houston route in Texas without safety drivers onboard, marking a historic milestone for the industry. Aurora has expanded operations to include nighttime driving, which more than doubles truck utilization potential. The company now operates three driverless trucks and has surpassed 20,000 driverless miles. Operations include a Phoenix terminal, enabling autonomous hauls on the Fort Worth to Phoenix lane for customers Hirschbach and Werner [source].
Bot Auto	Running driverless freight pilots in Texas since early 2025, a small (~4) fleet of retrofitted trucks in hub-to-hub operations. These driverless pilots are focusing on proving unit economics before scaling up. [source]
Einride	Swedish company Einride operates driverless trucks (pods) in multiple European countries. In September 2025, Einride completed its first fully autonomous heavy-duty truck operation on a public road in Belgium at the Port of Antwerp-Bruges. Einride uses a human-assisted autonomy model with remote operators who can control vehicles when necessary, enabling operations with "less than one remote operator per vehicle" [source].
Gatik	Autonomous middle-mile logistics company Gatik will operate on short-haul, middle-mile routes of approximately 40-50 miles, moving both dry and perishable goods to Loblaw stores in Canada. Deployment is planned towards the end of 2025 (20 trucks) [source].
Plus SuperDrive	Plus SuperDrive is being tested on public roads in the U.S. (Texas) and Europe (Sweden) with safety drivers onboard. It is developed in partnership with major OEMs including Hyundai, Iveco, and the TRATON Group (Scania, MAN, and Navistar). The technology is expected to move towards commercial deployment with a targeted launch in 2027 [source].
Pronto+VTTI	Cross country and port queuing was tested in the US, where gathered data is also made publicly available as a part of CONOPS project. A focus was placed on assessing the road readiness for automation, from physical and digital infrastructure perspectives [source].
Scania (HAVI Supply Chain)	The autonomous truck is being tested on a 300 km route between Södertälje and Jönköping in Sweden. The pilot involves hub-to-hub operations, with the first and last mile handled by manually driven vehicles. This project is a collaboration between Scania and HAVI Supply Chain, aiming to evaluate the effectiveness of autonomous technology in logistics [source].

Among these deployments, Aurora and Einride appear to be the longest operating companies, starting in 2017 and 2016 respectively. Aurora collaborates with technology partners Continental (automotive hardware for mass production), NVIDIA (computing) and PACCAR (base trucks) to develop the end product.

In contrast, Einride relies mostly on in-house development since the trucks are bot-like vehicles designed by Einride themselves, only relying on NVIDIA's computing power. Apart from hardware, the operation of these vehicles also differs particularly in fallback mechanisms. Aurora relies on automated safe stop algorithms on board and remote oversight (no teleoperation), whereas Einride uses remote operators to handle difficult situations through teleoperation. They also differ when looking at their partnerships related to operations. Aurora operates on interstate highways (hub-to-hub) and offers a driver-as-a-service model and collaborates with McLoed, a Transport Management System (TMS) software company. Meanwhile, Einride operates in ports, yards and short industrial roads and offer a freight-as-a-service model. They collaborate with Google Cloud (for Saga, an AI driven freight orchestration platform) and Maersk, tying into the European logistics chain. Their Control Tower platform for monitoring and remote operation is designed to integrate with freight orchestration for routing and optimisation.

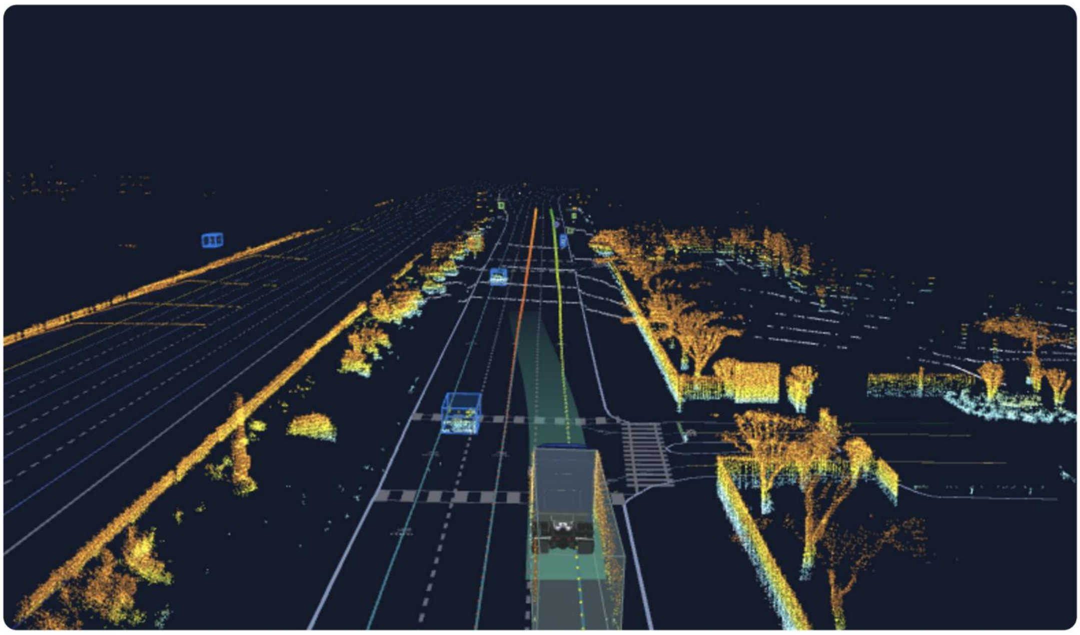

Figure 3: Aurora's vehicle planning and control platform 'Aurora Driver' perceiving the environment [3]

Aurora claims to have operated thousands of driverless miles so far with zero reported incidents that required emergency intervention. They have a defined operational design domain (ODD): clear weather, specific highway segments and specific destination locations; and claims to have a 'Verifiable AI' that combines deterministic, rule-based logic with adaptive machine learning and then proves compliance through formal verification and extensive testing. An independent validation by TÜV SÜD adds to these formal verification claims [3]. Despite this, three weeks after its commercial launch, Aurora added a human observer in the driver's seat (but not driving) at PACCAR's request due to prototype hardware concerns, which highlights a lack of confidence with OEM integration [source].

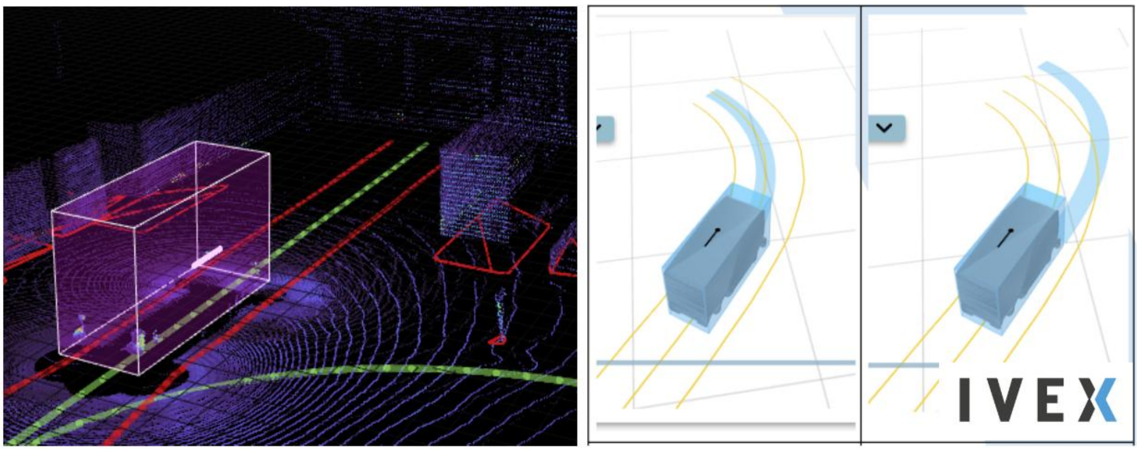

Figure 4: Einride's perception and IVEX's path evaluation [source].

Einride reports 97% uptime for its operations during all of its autonomous operations and remote interventions but does not publish failure rates or explanations about the remaining 3%. They partner with IVEX, a path planning and evaluation software provider that is also used by Euro NCAP [source]. Swedish audit agency RISE independently verified and confirmed satisfactory safety for the intended operation domain. The success of Einride has so far been in confined areas but looking at the research projects they are currently participating in the EU, operating beyond tightly controlled Level 4 ODDs remains challenging.

Estimating purchase price

Multiple academic sources indicate the acquisition cost of automated trucks to be around 25% higher than manually driven equivalents [4] [5]. That estimate is often used in their Total Cost of Ownership (TCO) analysis where driverless trucks and manually driven trucks are compared [6]. This 25% is claimed to be a pessimistic estimate.
Articles from market research reports such as in [7] and [8] provide hard number estimates. In [7], China and US based solutions are compared for various levels of autonomy. Table 3 shows an overview of these prices and price increase relative to SAE level 0 [source].

Table 3: Estimated purchase price comparison for autonomous truck.

Automation Level	China	USA
Level 0	$70,000	$114,286
Level 2/3	$112,000 (~60%)	$214,286 (~85%)
Level 4	$250,000 (~250%)	$450,000 (~295%)

In [8], a $50,000 to $100,000 difference is estimated from OEMs, and adds that automation companies often provide Driver-as-a-Service (DaaS) where customers buy or lease a truck and pay for virtual drivers by kilometre such as with Einride, Freight-as-a-Service (FaaS) where customers pay for transport of goods from A to B that is carried out by the automation company, or other real-time support as a subscription model alongside initial costs. Hence the actual fixed and operating costs will look different for each model. Moreover, the Level 4/5 trucks are also often electrically powered, which also add to the cost. Electric trucks themselves cost between €250,000 and €350,000, which is 2-3 times higher than diesel trucks [9].

Adding the 25% or the $50,000 to $100,000 difference mentioned to this range puts it in the range of Table 3's expected Level 4 automation. A consolidation of all these sources results in Table 4.

Table 4: Estimated purchase price for autonomous trucks.

Category	Estimated Price Range (EUR)
Diesel truck	70,000 - 150,000
Electric truck	250,000 - 350,000
Autonomous diesel truck (basic)	200,000 - 250,000
Autonomous electric truck (basic)	350,000 - 450,000
Autonomous diesel truck (advanced)	250,000 - 450,000
Autonomous electric truck (advanced)	450,000 - 650,000

2.1.2 Vehicles – private areas

The CAT4Yards tool considers terminal tractors (electric, diesel) and terminal tractors with no cabin as well as trailer mover archetypes. Compared to automation in public areas, this category of automation in private areas has had real world examples since around 1993 in the Port of Rotterdam, where Automated Guided Vehicles (AGVs) were used to move containers in the port area [source]. Despite a head start and relatively less legislation required to use automated vehicles compared to public areas, the shift from automated to autonomous is still taking place, where companies from China are seemingly advancing forward faster. Table 5 presents a list of CAT deployments that are pushing the state of technology further through commercial operations and research pilots.

Table 5: Selected list of notable yard and port automation deployments.

Company	Details
Fernride	At DB Schenker site in Tilburg, teleoperated yard tractors are being tested. This partnership is based on gradual autonomy, where teleoperation is first used as in intermediate step. Fernride obtained TÜV SÜD safety certification under the EU Machinery Directive and began rollout/driverless operations (for example at HHLA TK Estonia in July 2025).
ISEE+TICO	One of the first commercial deployments of autonomous yard trucks in the US starting February 2024 [source], ISEE's trucks integrate with yard and warehouse management, claiming minimal infrastructure changes. A notable advancement is their claim to have automated the trailer coupling with a robot, but this does not seem to be the case in their commercial deployment. Video demonstrations do show the capability of their technology [source]. They claim to have performed hundreds of thousands of autonomous trailer moves as of April 2025. They have also received third party cybersecurity certification, which adds some validation of their solutions. They have received about $70 million in funding so far.

Outrider	A direct competitor of ISEE, Outrider also deploys its solutions to Fortune 500 companies in the US, with an operations-as-a-service model. However, Outrider also provides solutions in warehouse and public road automation, which makes their focus broader. The company is currently in the process of scaling up their solutions and safety certifications. TÜV SÜD conducted preliminary assessments. They partner with Orange EV to develop a zero emission autonomous yard tractor [source].
Terberg + Oxa	Terberg makes the AutoTUG platform, which is a drive by wire ready electric tractor. Automation provider Oxa (StreetDrone) have been testing autonomous solutions at the Port of Rotterdam, but these are not yet commercial deployments.
Terberg + Embotech	Another port in the Rotterdam area (APM Terminals Maasvlakte II) has committed to 30 autonomous electric terminal tractors, starting operations in 2027. The companies claim to have successfully piloted the solutions already at the site.
VDL + Akkodis + Medrepair	At the port of Antwerp-Bruges, VDL and their partners have conducted demonstrations of intra-terminal autonomous transport using VDL's 3-axle MTT platform which has no cabin.
VDL+Aviko	Although not fully autonomous, VDL's special vehicle at Aviko factory transports pallets of goods to a cold storage facility nearby. The vehicle follows predefined routes but has awareness of obstacles. It adheres to ISO 3691-4 which defines safety standards for driverless trucks.
Westwell	The Chinese company mainly operating in Asia, 6 autonomous yard tractors (Q-Trucks) have been used in day-to-day operations since 2020 in Thailand's Hutchison port. This makes the deployment the world's first to achieve a mixed operations of manned and unmanned vehicles [source]. They have also committed to 100 electric Q-Trucks at the port. They have also expanded in Europe, at the Port of Felixstowe where 34 electric units are already deployed, making it the first port in Europe to introduce autonomous mixed traffic operations.

The list above is not exhaustive with numerous deals being made quite often all over the world. For example, deployments in the middle east and Asia by ZF Group and Einride are also in plans.

AGVs are a mature technology, widely adopted for decades in structured terminals, with incremental innovation over the years for better navigation, fleet orchestration, predictive maintenance, etc [10]. These driverless, flatbed vehicles without a cabin move containers often with transponders in the ground and now also with GPS/LiDAR. They have been proven to be safe and efficient but require expensive infrastructure modifications and tight integration with adjacent systems, making them harder to retrofit into existing non-automated terminals. Furthermore, adapting to exceptions or ad-hoc moves are a challenge with such rigidly controlled machines [11].

Automated terminal tractors on the other hand are often standard yard tractors fitted with sensors, drive-by-wire kits, and autonomy stacks (Outrider, ISEE, StreetDrone, etc.) that require relatively less infrastructure modification. They have been in operation commercially relatively recently and scaling efforts are now ongoing.

Given that they can be based on existing tractor models and feature more vehicle-level intelligence, they are easier to integrate into existing yards and can work alongside mixed human traffic and offer fallback to human driving with the presence of a cab. Automated (retrofit) tractors are designed to fit into existing mixed-traffic yards with conservative autonomy, human fallbacks, and lane/operational rules. Hence, they rely heavily on geo-fencing, remote supervision and human intervention for edge cases. Next-gen cab-less autonomous vehicles aim for higher autonomy and more robust perception stacks so they can operate without dedicated separation. Westwell, Terberg, and Einride's pilots in Sweden/US have already shown that the vehicle technology *can* work in controlled environments, but the fleets are still counted in tens rather than thousands like AVGs.

The scaling is often more difficult since the technology is still not mature:

- Without a cab, the autonomy needs to be very robust since the human driver fallback is not possible. This requires high-quality mapping, use of digital twins and interaction with multiple other systems. Scaling safe remote-operations to handle many simultaneous exceptions is still under development, as evidenced by the numerous research projects in this area.
- Handling adverse weather consistently is only now being solved in research projects but fundamentally require redundancy in sensors and fallback mechanisms that add to capital and operational costs. Commercial deployments are restricted to strict weather thresholds. Reliably detecting unusual obstacles (e.g. dangling straps, plastic sheets, or humans partly hidden behind cargo) is also a fine detail to improve on (source).
- In case of yard tractors, coupling automation (connecting the tractor to trailers) is a bottleneck, and the technology still lacks the ability to deal with exceptions and precision manoeuvres in mixed yard use [12].
- The SAFE20 project showed that automating swap body movements fared better than trailers, since the latter required additional procedures by personnel to handle trailer connections or use automated coupling equipment, both have negative impact on profitability.

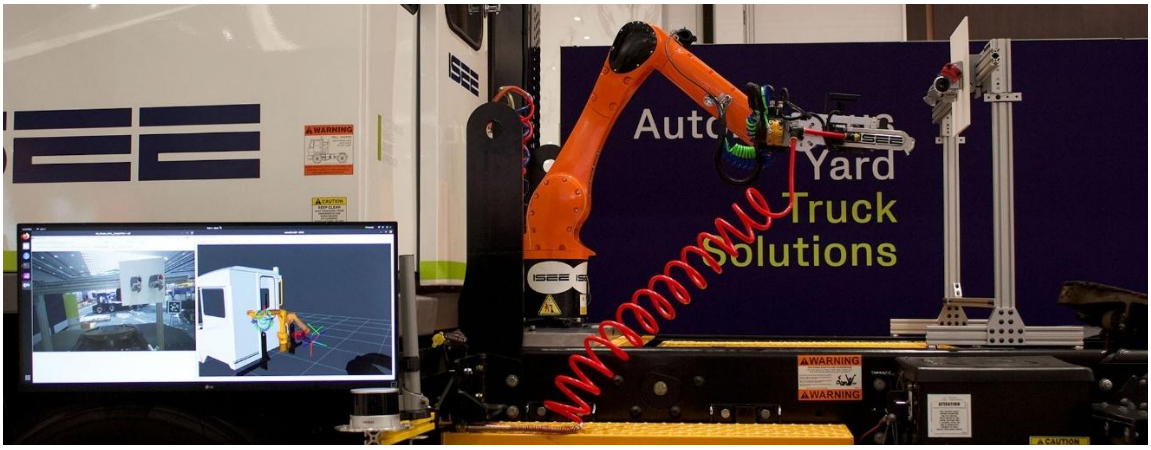

Figure 5: ISEE's robotic arm solution for tractor-trailer coupling (source).

- Scaling operations that require teleoperation support also puts excessive cognitive load on teleoperators, who need to deal with possible latency fluctuations, frequent context switching, etc., but tele-assistance with abstracted commands may help this [13].

Estimating purchase price

Similar to estimating purchase price of public road automation, several sources of information are considered for CAT in private areas. Information from industry experts working on trailer mover and tractor automation in EU and national research projects, market research reports [14], and academic sources such as [15] and [5], are considered to create a list of current (2025) purchase prices.

Table 6: Estimated purchase price for autonomous tractors and trailer movers.

Category	Estimated Price Range (EUR)
Electric trailer mover	80,000 - 110,000
Autonomous electric trailer mover	~200,000
Diesel terminal tractor	70,000 - 150,000
Electric terminal tractor	150,000 - 250,000
Autonomous electric terminal tractor cabin	350,000 - 700,000
Autonomous electric terminal tractor no cabin	450,000 - 800,000

Apart from purchase costs, operational expenses also differ per vehicle type. Available information has been tabulated and presented in Appendix B – Operational Costs.

2.1.3 Control tower (fleet/orchestration & safety)

TOS (Terminal Operating System - e.g., Navis or the port's in-house TOS) allocates container moves and berths. Yard Management System (YMS) provides yard-level slotting and trailer/container status and a Fleet Manager / Orchestration Layer (vendor or in-house middleware) consumes TOS/YMS tasks, schedules vehicle missions, optimises routes, and pushes commands to vehicle autonomy stacks [16].

As seen with Port of Rotterdam and Outrider deployments, the Control Tower / Mission Centre monitors the fleet, handles exceptions and performs teleoperation when autonomous logic cannot proceed (shown in Figure 6). The control tower has dashboards that combine TOS job queues with live fleet state (position, health, battery, sensors) and the ability to reroute, pause, or assign manual teleoperation takeovers. The tower or control room is the human-in-the-loop orchestration layer that closes the loop between planning (TOS/YMS) and execution (vehicles) [17].

Figure 6: Operator controlling a truck remotely from a control centre in the yard (source)

The SoTA shows that operators in the control tower/room are split into mission schedulers, teleoperators, safety officers and network engineers. To facilitate these roles, digital twin layers to visualize vehicle intents, modules for scheduling, diagnostic, etc., need a low latency and redundant networking and computing resources. Such networking is further described in sections 2.1.5.

In the current deployments, CAT companies follow various approaches to integrate control towers. Einride has cloud-based supervision hubs with remote teleoperation without the need for any presence in the site's control room, and only edge-computation nodes need to be placed on-site for safety backup. Fernride and Aurora employ similar 'distributed control' architectures, with remote operators linked to the vehicles by low-latency networks. Fernride has a teleoperation centre at their office in Munich that controls their fleets in various sites but also support on-site local control pods.

The main challenges presented in studies are that scaling teleoperation stations is not feasible, so abstraction of vehicle tasks is required to achieve desired operator-to-vehicle ratios. To ensure redundancy and reliability redundant power supplies, fail-safe network paths and local emergency stops are required; network outages and degraded video streams can cause safety issues, so redundancy is necessary but adds cost and complexity. Hence, on-site control rooms that monitor and manage automated fleets are typically seen in ports and terminals rather than in yards since the former already have provisions for redundancies. Yards tend to rely on cloud-based services provided by the automation companies. Retrofitting control tower hardware specific to automation technology is costly. Interoperability with TOS/YMS is complex because vendor specific Application Programming Interface (APIs) are not standardised which requires the automation providers to make custom integration with the existing tools at the site. Cybersecurity concerns surround high-value targets like the control tower because it is a single point of attack surface for the whole automated operation, where private networks are preferred with encrypted communication.

2.1.4 Physical infrastructure (site readiness)

For any CAT implementation, the physical infrastructure is a major enabler and hence can be a fundamental bottleneck. Considering a completely new or currently manually operating site, the following aspects need to be considered in the physical infrastructure of the operating environment [18] [19]:

- Connectivity hardware: Wired and wireless networking hardware needs to be planned to offer enough coverage and bandwidth in the operational area for the use cases. Connectivity is hence not only a digital concern but also physical installation at the site. Such infrastructure planning is tackled by using digital-twin simulations where the use cases are simulated in the virtual world and the required road-side sensors, beacons, routers, etc., can be planned strategically. Additionally, routing wired communication for required ethernet-based networks linking edge devices and to the control tower, power supplies for smart edge-devices, etc., need to be considered. This physical planning is based on the digital requirements.
- Perception and localization support: Although vehicle localization often uses on-board sensors, depending on the automation level and type, ground-based beacons (UWB, RFID, magnetic markers) are used.
- Traffic and Yard design: Many CAT deployments start with fenced or semi-exclusive routes for automated vehicles. This involves integration of smart intersections/lights and redesigned gate areas that need additional instrumentation (RFID, UWB, cameras, weigh-in-motion, etc.)
- Energy and maintenance: Large CAT fleets need consolidated (fast) charging bays that can also be automated (robotic connectors or inductive pads). CAT vehicles require frequent sensor cleaning and calibration that require dedicated working spaces.

As listed in section 2.1.2, several of those sites made changes to infrastructure to enable CAT. Port of Rotterdam started with dedicated automated container lanes with embedded transponders in the ground and later replaced with GPS+LiDAR and smart edge-devices. The Port of Felixstowe deployed a private 5G network meaning installing several antennas and radio hardware, and dedicated charging infrastructure. DB Schenker in Tilburg adjusted the control room to house teleoperation stations that are integrated with YMS, installed camera upgrades in loading bays for better situational awareness, and marked priority lanes for teleoperated traffic. Port of Antwerp-Bruges demonstrators required geo-fenced intra-terminal roads and safety barriers to separate mixed operations. UWB anchors were placed where GPS was unreliable near stacks and cranes.

Existing sites often are not designed with sensor occlusion in mind and have inconsistent lane markings, since they are optimised for humans, not machine perception. They face uncertainty in deciding what exact lane widths, surfaces, and markings will be needed for universal operations, but standardisation in this field is not universal. Physical segregation of human workers and automated vehicles (often required for safety certification) takes significant re-planning of operations. Implementation efforts are often done gradually, by retrofitting new CAT infrastructure into workflows before scaling. This staged method is more manageable and avoids shutting down operations but is more expensive per m^2. Since autonomous vehicle technology is evolving fast, site owners struggle to plan CAT investments and integrations among increasingly busy operations.

2.1.5 Digital infrastructure & integration with transport management

CAT vehicles heavily rely on the digital infrastructure in the form of vehicle assistance (sensors for perception and computation for autonomy), roadside devices and operational control for traffic management. The state of maturity of digital infrastructure varies for ports/terminals and yards since port environments have been using AGVs since decades while automation in yards is relatively modern technology. In ports and terminals, the concepts of a Terminal Operating System (TOS) and Equipment Control System (ECS) are used to categorize the layers of digital operation, as shown in Figure 7 [17]. These layers eventually control the operation of Container Handling Equipment (CHE) like cranes and vehicles.

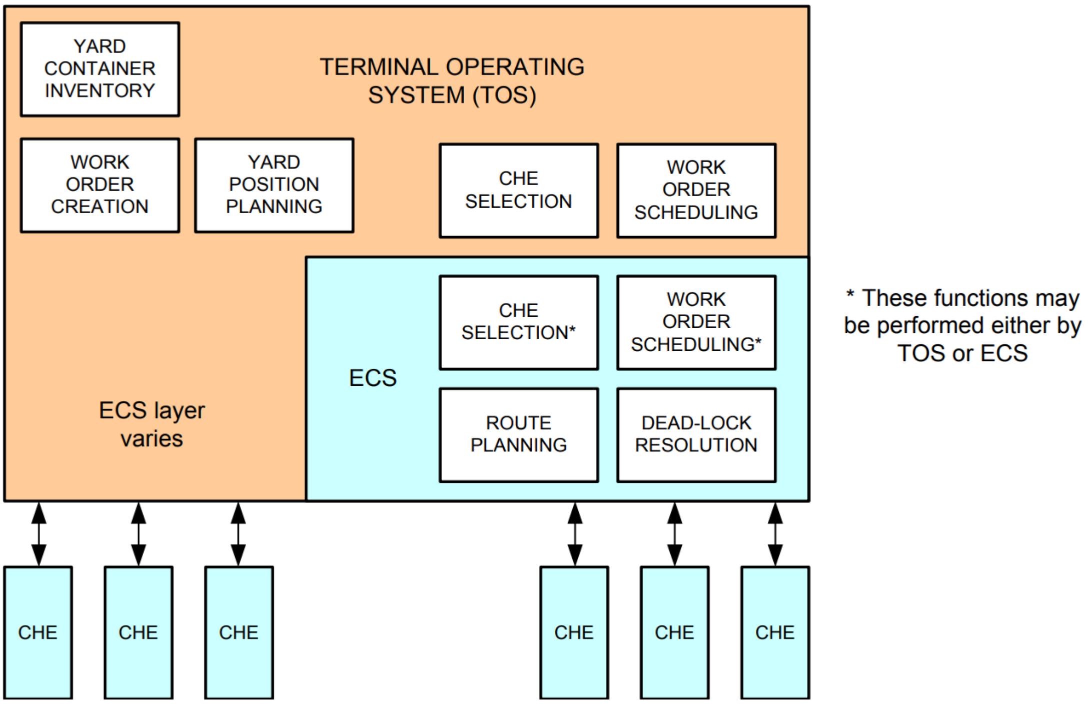

Figure 7: Layers of digital operations in ports and terminals [17]

The TOS software controls the high-level logistics of a terminal, including key functions such as vessel planning, container inventory maintenance, job order creation and gate operations. Container Handling Equipment (CHE) can be manned or unmanned (automated), such as yard tractors and cranes. A group of automated vehicles may share a common software control module ECS, where its role is to handle coordination and interaction between different types of automated CHE (yard tractors, cranes, etc.). The ECS also focuses on local routing decisions. Traditionally magnetic strips in the ground, GPS, RFID markers or Bluetooth beacons for vehicle localization are being used. Communications from the vehicle and infrastructure sensors to the ECS and TOS are communicated via Wi-Fi, private LTE, 5G networks, OPC-UA over Ethernet, etc. using proprietary APIs specific to the implementing terminal or technology provider. Reports such as in [17] and [20] mention the lack of generalised standards in this space, where the vendor selected for a certain project will have to be a long term partner and is difficult to switch supplier technology since integration is custom-built based on the specifics of each tool.

When looking at yards and distribution centres, a Yard Management System (YMS) manages the movement and storage of trailers and containers within the yard [21]. YMS software performs real-time asset tracking using RFID tags, GPS, or barcode scanning, dock scheduling and has management features, shipment prioritization capabilities, and gate management functionality. The YMS is analogous to the TOS. Fleet orchestration is typically vendor specific that is designed to integrate with YMS in a case-by-case basis in each deployment. Given the data flow that automation providers in yards have access to is significant, they often also offer YMS capabilities.

<u>Data exchange standards in logistics</u>
Generally, in logistics while multiple standards exist for communication between yard management, warehouse management, and terminal operating systems, the industry continues to use a mix of traditional Electronic Data Interchange (EDI) standards (UN/EDIFACT, ANSI X12), modern Business Object Documents (BOD) approaches, and non-standardised API-based integration methods. The standard used often depends on the age of the systems, regional preferences, and specific industry requirements [source]. As logistics operations become increasingly complex, the trend is moving toward more flexible, non-standardised API-based integration approaches while maintaining support for established EDI standards to ensure backward compatibility.

Despite these established standards, several challenges persist in yard-warehouse-terminal system integration:

- Legacy System Limitations: Older systems may lack support for modern integration standards, general support, security, maintainability, etc.
- Data Quality Issues: Poor data quality can hinder effective use of systems
- Real-Time Visibility Gaps: businesses and processes struggle with the absence of real-time data across systems
- System Compatibility: Fragmented IT systems and isolated operations make integration difficult

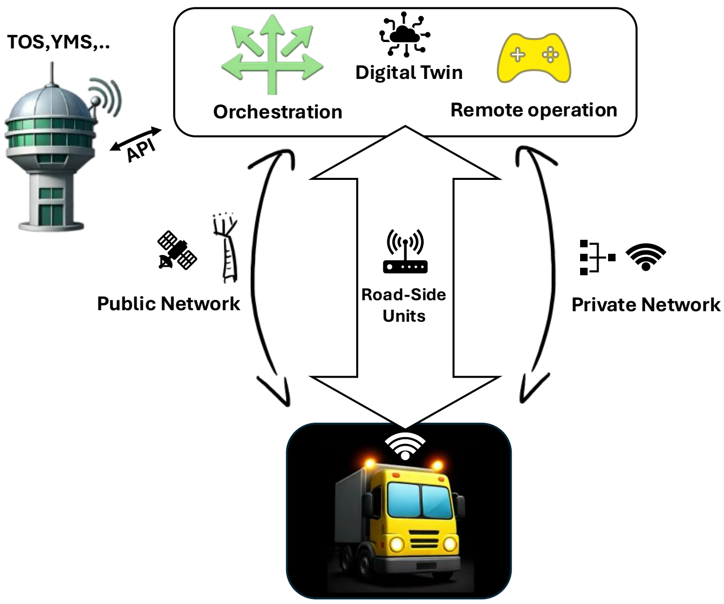

Figure 8: General overview of digital infrastructure used in CAT.

In order to have a basis for analysing in detail the SoTA related to digital infrastructure of CAT in general, the scheme shown in Figure 7 and details of deployments of CAT mentioned in section 2.1.2 are used to generalise the operations from a digital perspective, as shown in Figure 8.

The structure is layered vertically:
- Top layer can be considered as ‘Orchestration and monitoring’ that deals with fleet planning, routing, remote teleoperation/assistance and digital twin decision making. This layer must communicate with the site’s existing or new management systems often via custom APIs.
- The mid-layer can be considered as the ‘Connectivity and support’ infrastructure that mainly serves the communication between the top layer and the CAT vehicles. The communication is facilitated in numerous ways, either through public networking infrastructure from telecommunication providers or via private networks (wired or wireless). This is also the layer that hosts Road-Side Units (RSUs) that support the automation with sensors, computing, and traffic control hardware.
- The lower level would be the vehicle’s local intelligence and communication hardware.

Deploying CAT of any kind at a site involves satisfying requirements in each of the three layers, which have numerous units and modules of systems as shown in Table 7. Vehicle level technology has been extensively covered in sections 2.1.1 and 2.1.2. The following sub-sections go over the top and middle layer details.

Table 7: Overview of digital infrastructure modules used in CAT

Layer	Unit	Module	Purpose
Orchestration and monitoring	Vehicle management	Fleet management, routing, digital twinning, teleoperation	Offers user control of the vehicle fleet
	Enterprise management	TOS, TMS, YMS, WMS	Offers user control of site operations
Connectivity and support	Networking	Public LTE/5G/6G (experimental)	Enables communication between vehicle, edge nodes and orchestration.
		Private 5G cell	Enables communication between vehicle, edge nodes and orchestration.
		Wired	Enables communication between RSUs, edge nodes and orchestration.
	Road-Side Units	Sensors (RTK base station, UWB anchors, cameras, etc..)	Supports the operation of vehicle from perception perspective
		V2X/traffic control	Provides rules for traffic control
	Edge nodes	Edge computing node	Provides resources to run demanding tasks like sensor fusion, mapping, digital twinning, without needing to send data to distant servers.

		Wi-Fi routers	Enables communication between vehicle, edge nodes and orchestration.
Vehicle	Platform	Base drive-by-wire vehicle	Platform to build autonomous systems
	Intelligence	Automation control hardware and software	Provides vehicle level intelligence and communication

2.1.5.1 Orchestration and monitoring

Consider the scenario that a site has partnered with an Automation Provider (AP) such as Embotech, Einride, Outrider, etc. The vehicle could be either from an OEM providing drive-by-wire ready platforms or could be a product of the AP themselves. The top layer of operations of these vehicles is typically not possible without the AP's own management software since the deployments are done vertically, where the AP provides:

- The vehicle (hardware & sensors),
- The vehicle control stack (local autonomy, safety envelope),
- The fleet orchestration software,
- The teleoperation interface, and sometimes
- The RSUs and connectivity backbone.

For example, Outrider has its own orchestration system, teleoperation centre, and even yard management integration; Westwell uses Qomolo AI Logistics System (QALS) which is their proprietary digital twin and orchestration system; Embotech provides its own ProDriver Control for motion planning and ProFleet Orchestration for coordination. This can be deployed either within the control tower/room of the site or partly remote from the APs centres. Hence, the currently available market solutions of CAT rely on vendor-dependent management software suite, that is made interoperable with other enterprise tools, or in some cases the APs provide an end-to-end turnkey solution including all TOS/YMS/WMS capabilities.

\However, there are emerging pilots (research) that aim to create interoperability in orchestration tools such that it is vehicle automation provider agnostic. Pilot deployments in the Port of Antwerp for example, is continuing research and development of open API standards for handling automation in the port, often with partners contributing in all layers of the infrastructure. These standards revolve around abstracting automation commands and using open source 'Application Layer' technology that enables sending and receiving data, e.g. Robot Operating System 2 (source), the VDA5050 jointly developed by the German Association of the Automotive Industry (VDA) and others (source). There are also ISO standards that are relevant here, like ISO 23793 that defines AGV fleet management communication, but it is structured mostly for indoor operations and semi-structured environments and does not fully encompass the highly dynamic possibilities of CAT.
The ISO 3691-4 defined vehicle level safety rather than broader integration.

Although some progress is being made in interoperability in this layer, the norm appears to be still vendor dependent vertical integration. APs certify their vehicle and control package as a whole since ISO 3691-4 defines operations of a 'vehicle system', exposing the encrypted communications to third party tools and replacing the orchestration modules may impact that certification. This bottleneck is logically beneficial to the APs since they get to provide large amount of services on top of the vehicle alone.

Interoperability in machine control/orchestration usually follows the chronological order of vendor proprietary tooling, customers and integrators making custom middleware for interoperability, pressure from customers and regulators to have native interoperability, vendors finally allowing limited access to control. This is evident from industrial robots where ROS (source) and OPC-UA (source) emerged as real solutions for interoperability. In indoor warehousing automation, AGV interoperability was taken seriously by vendors after big customers demanded it (source).

2.1.5.2 Connectivity and support infrastructure

Given the scenario of AP providing vehicles and top layer management tools, the middle layer of connectivity is the area where variation in deployment is possible. Numerous ports and industrial areas partner with network providers to enable automation and digitalisation. For example, Port of Antwerp partners with Telenet and CityMesh, and Rosslare Europort in Ireland partners with Vodafone. Cutting edge 5G and (emerging) 6G technology are being deployed for these environments. These dedicated networks are for port use, where network slicing segregates the available core bandwidth to various actors (like CHE). The operating cost of such a dedicated network tower is about €50,000 per year (based on estimates from an industry expert).

The networking layer deployed by commercial operations and research pilots show numerous options:

- Outrider: Uses their own ruggedized Wi-Fi 6 network for vehicle telemetry, switching to LTE fallback for connectivity redundancy. The hardware is provided by Outrider and is installed by the yard operator.
- VDL at Aviko site: Operates entirely on industrial Wi-Fi linked to the factory's SCADA system, no telecommunication used.
- Westwell, Einride, Fernride: Use private 4G or 5G network available at the site provided by the site's telecommunication partners.
- Pilots: Public 5G networks are not reported to be used in CAT commercial deployments, but research project especially covering cross-border, cross-private boundary scenarios use public networks often with network slicing and smart orchestration of bandwidth. Research and standardised APIs are being developed for multi-access edge computing and bandwidth allocation with 5G/6G based networks [source]. Hence, the use of public networks is ongoing research that is not yet commercialized. The pilots often combine networking with edge computation together in a RSU.

Apart from networking, the operations of CAT vehicles rely to varying degrees on supporting infrastructure such as Real-Time-Kinematics (RTK)-bases for localization, edge nodes for complex computations related to trajectory planning and digital twinning, and site specific V2X related tasks (gate commands, traffic control at intersections, etc.). Generally, in the field of intelligent transport technology, the communications between vehicle and surrounding systems are known as V2X (vehicle to everything) communications, which have more standardisation initiatives relevant to CAT in mixed traffic scenarios [22]. Such technologies are gaining usage in CAT scenarios, where the legacy techniques are unable to cope. V2X provides a mesh network, while the traditional techniques are point-to-point communication, allowing the former to be far more flexible, while the latter focuses on reliability alone.

The costs related to Roadside Units (RSUs) for Vehicle-to-Everything (V2X) communication vary significantly depending on the technology, deployment scale, and additional infrastructure needs as shown below.

Table 8: Roadside Unit (RSU) costs [23].

Component	Estimated Cost
Basic RSU hardware	€4,000–€7,000 per unit
Intersection Deployment	€26,000–€30,000 per intersection
Annual Maintenance	~€1,000 per unit

2.1.5.3 Overview of integration possibilities

Based on the findings in the various layers of digital infrastructure, Table 9 shows which party is typically responsible to integrate the various modules and what interfacing methods are used. Although various options exist in networking, interfacing is relatively simple since regardless of the underlying radio frequency since the Internet Protocol (IP) techniques remain the same and hence that layer can be abstracted. Naturally, APs can specify required latency and bandwidth requirements if the network. The same holds for edge computation resources.

Table 9: Overview of layered integration of digital infrastructure

Layer	Unit	Module	Integrator	Interfacing
Orchestration and monitoring	Vehicle management	Fleet management, routing, digital twinning, teleoperation	Automation Provider	Mostly proprietary, some emerging standards like VDA 5050, ROS, OPC-UA
	Enterprise management	TOS, TMS, YMS, WMS	Site responsibility, but interface with automation provider for integration.	Mostly custom APIs based on EDI standards
Connectivity and support	Networking	Public LTE/5G/6G (experimental)	Site's Telecom/integration partner	Open APIs for smart features
		Private 5G cell	Site's Telecom/integration partner	Simple integration since network layer can be abstracted
		Wired	Site, with requirements from Automation Partner	Wired networking (Ethernet based) is common
	Road-Side Units	Sensors (RTK base station, UWB anchors, cameras, etc..)	Automation Provider	Mostly proprietary
		V2X/traffic control	Site	V2X standards are available but are evolving

	Edge nodes	Edge computing node	Automation Provider or integration partner	Relatively simple since computing hardware can be abstracted.
		Wi-Fi routers	Site or Automation Provider	Simple integration since network layer can be abstracted
Vehicle	Platform	Base drive-by-wire vehicle	OEM or Automation Provider	Proprietary
	Intelligence	Automation control hardware and software	Automation Provider	Proprietary

2.2 Logistics & People

2.2.1 Traffic management (fully automated vs mixed traffic)

V2X technologies are increasingly integrated into yard management systems to optimise traffic flow. The strategies used for the management of fully automated traffic and mixed traffic are inherently different due to the added complexity of human driven vehicle behaviour and vulnerable road users around CAT vehicles.

<u>Fully Automated Traffic Management Systems</u>
AGV safety standards like the ISO 3691-4 specifies restricted, confined and hazard zones for speed control and feature personnel detection, but multi-vehicle interaction is not defined in the standard [24]. In fully automated yard environments, traffic management relies on control systems that coordinate all vehicle movements with precision and efficiency. Systems such as Konecranes TEAMS ECS, Navitec Systems, Rocla FleetController, etc., have been in operation in fully automated terminals where AGVs are deployed. More recently, Outrider's Mission Control is a cloud-based example of this, where machine learning techniques like reinforcement learning are increasingly being integrated alongside simple but robust algorithms. As driving mileage increases, more data is available for the training of these machine learning algorithms.

- **Centralised Control Systems**

Most fully automated terminals employ centralised traffic management through an ESC and/or TOS. These systems function as the "brain" of the operation, coordinating all automated vehicle movements across the terminal.

The primary functions of these centralised systems include:
- Route planning and optimisation for each vehicle
- Real-time tracking of vehicle positions and status
- Traffic conflict resolution through mathematical optimisation
- Resource allocation to maximise operational efficiency
- Job scheduling and dispatching to vehicles

For example, Outrider's Mission Control represents a modern cloud-based management system that dispatches and monitors multiple trailer movements simultaneously, either onsite or remotely, working standalone or integrating with other supply-chain software [source].

- **Conflict Resolution Mechanisms**

A critical aspect of traffic management is how to handle situations where multiple vehicles need to cross paths or access the same area where specific coordination strategies are employed [25]:

- Predetermining crossing orders at conflict areas through optimisation algorithms
- Dividing routes into segments (as small as 2 meters) for precise control
- Prioritising vehicles based on their tasks and time constraints
- Using mathematical models to minimise delay at destinations

These algorithms typically aim to optimise the overall system performance rather than individual vehicle efficiency. For instance, at container terminals, the goal might be to minimise the delay of AGVs at their destinations and improve quay crane productivity. Conflict resolution is enabled by V2V and V2I communication.

Vehicle-to-Vehicle Communication (V2V)

In advanced systems like those deployed by VDL, ISEE and Outrider's fleet management systems, the decentralised V2V communication allows AGVs to inform each other about their planned actions. Using dynamic path planning, this enables them to drive closer together, reducing waiting times between trips and increasing container throughput per vehicle [source]. Videos are also published on such operations taking place in practice [source].

Mixed Traffic Management Systems

Managing environments where automated and manual vehicles coexist presents unique challenges requiring specialized approaches. This area of technology relies more on the V2X communication and on-board sensors on the vehicle. Autonomous vehicles often use a multi-modal sensor fusion approach to gather rich data about the surroundings and locally adjust their planned trajectory. Manually driven counterparts need to be notified about the presence of autonomous vehicles and should get clear instructions on how to participate in traffic.
VDL's Mixed Traffic Transporter (MTT), ISEE AI and others uses a "multi-modal sensor fusion approach" to position vehicles along their intended path while anticipating other road users [source].

- **Speed Harmonisation**

Research indicates that harmonising speeds between automated and non-automated vehicles is crucial for safe mixed traffic operations. Studies suggest limiting both automated yard tractors (AYTs) and road trucks to around 20 km/h to create a safe traffic environment [26].

This speed harmonisation provides:

- Optimal vehicle utilization
- More harmonious traffic flow by dampening speed oscillations

From the sources, it appears always the case that when autonomous vehicles are present in the yard, speed limits of all vehicles are reduced to around the 20 km/h mark.

EasyMile EZTow operates at 15 km/h, the ISEE autonomous trucks at 18-20 km/h, with a further dynamic reduction of speed during adverse weather conditions (rain/fog), pedestrian proximity and while reverse manoeuvring.

- **V2V and V2I techniques**

Manually driven vehicles are notified of the presence of autonomous vehicles either in the way of having a tablet device, Variable Message Signs (VMS) displaying the intentions of the nearby autonomous vehicle, audible alerts, etc. This is enabled by V2V communication. Using V2I communication, smart traffic lights are controlled based on priority allocation where a centralised system such as the TOS determines right of way based on various factors. Various algorithms exist that optimises the decision-making [26].
Practically, different ports have implemented their own mix of traffic rules. Some use color-coded lighting to dynamically assign lane usage to manual or autonomous traffic,

- **Teleoperation as a Transitional Approach**

An emerging solution for mixed traffic is teleoperation, where human operators remotely control vehicles. Fernride's approach combines human capabilities with autonomous technologies by equipping electric trucks with sensors and cameras that allow drivers to operate vehicles from workstations hundreds of miles away.

This method:

- Represents a stepping stone toward full autonomy
- Enables human intervention when needed
- Allows integration of automated trailer shunting into ongoing operations

While there are scattered yet comprehensive standards for automated vehicle safety (e.g., ISO 3691-4, German VDI 2510) defining interactions with surroundings and intersection requirements, specific standards for traffic management at intersections in automated yards are still evolving. Current best practices mentioned in this section are typically used because they combine elements from available standards and research-based algorithms and techniques. Hence, they are often tailor made to the use-case of the site by the technology provider.

2.2.2 Tasks & skills of people

Adopting CAT shifts work from manual driving/handling to supervision, orchestration, teleoperation, system-integration, data/telemetry monitoring and safety governance. That requires new digital, telecom, safety and human-factors skills, plus organisational changes (new roles, different staffing patterns). The main problems are operator workload & situational-awareness limits, training gaps, poor human-machine interfaces, union/organisational resistance, recruitment of hybrid skillsets, and coordination across multiple stakeholders (source).

Transitioning from manual operations and legacy workflows to automated operations involves challenges in implementation:

- Operator cognitive overload, situational-awareness limits and teleoperation scalability:
  Teleoperators lack natural depth cues and must rely on cameras/sensor overlays; this increases mental workload and reduces performance when handling multiple vehicles. Studies recommend high-level commands and better user interfaces to mitigate the issues, but the problem persists. Teleoperation at joystick level doesn’t scale.

Research & pilots show that abstractions are needed so one operator can supervise many units — but designing safe abstractions is still active research [27] [28].

- Skills shortage & re-skilling needs:
  Ports often lack staff who combine domain knowledge (terminal operations) with telecom, data and software skills. Training programs are limited and on-the-job learning remains the norm (source). A survey of 40 global ports showed that switching to automated operations typically reduced operating costs, but reduced overall productivity by 11% (source). The main pitfalls were a shortage of qualified engineers, lack of quality data, insufficient collaboration between different parts of the port, and the presence of a large number of non-standard operations.
- Organisational & labour relations friction:
  Workforce and labour unions are resisting change, citing fear of job losses and blaming automated terminals for failing to cope with supply chain challenges such as the Covid-19 pandemic (source). Interviews with dockworkers showed that they are not "anti-technology", but have concerns about democratic decision-making in implementing automation (source).
- Training & certification gaps:
  There are few standardised curricula for teleoperators, fleet managers or digital yard technicians. This creates inconsistent competence and makes cross-site scaling harder (source).

2.3 Organisation

2.3.1 Responsibility & ownership (governance)

The investment into CAT technology typically involves a collaboration between the site owners and numerous technology providers often providing services in a subscription model. This shifts the balance of ownership out of the local economy and can cause fragmented responsibility, as highlighted in a US-based survey (source).

The common themes from that survey and results published in [29], we can conclude:

- Joint attribution of responsibility: Without a clear definition of responsibilities, CAT sites may face disputes among departments and lack of oversight by port/site authorities (private service providers take over part of their oversight). Automation projects require shared governance among port authorities, terminal operators, unions/workforce, and government regulators. No single actor can manage safety, workforce, environmental and operational aspects alone.
- Transparency & metrics: Operators often overpromise benefits and underreport failures, leading to mistrust. Ownership includes being responsible for measuring outcomes (efficiency, safety, job impacts), making that data visible to stakeholders, and adjusting policies/responsibilities based on that feedback.
- Regulation & legal liability: Who is responsible if something goes wrong (accident, job loss, environmental harm)? Clear legal responsibilities (permits, safety approvals, insurance) must be assigned.
- Infrastructure investment responsibility: Who pays for physical infrastructure (roads, signals, network, edge computing, sensors, etc.), for up front and ongoing maintenance? This lack of clarity is amplified due to concerns about legal liability and responsibility and hence slows deployment.
- Accountability of workforce training: Unions advocate for being trained with new skills, but there is often a lack of clarity on who is responsible/pays for this training.

2.4 Laws and Regulations

Industrial sites, terminals and private roads are not governed by the traffic and road laws in the same way as public roads; owners can deploy AGVs, automated tractors and cab-less vehicles subject to workplace/safety law (occupational health & safety), contractual rules, and applicable standards (e.g., ISO standards). On public roads, understandably the scope of operations is far more limited.

The Netherlands has been leading the unification of EU regulations on public road vehicle autonomy since 2016 and was one of the first EU member state to have national regulations to conduct on-road experiments with autonomous vehicles. In the *Actieagenda* of 2024, the Ministry of Infrastructure and Water Management described that policy and legal frameworks are being set up for automated transport to be tested on public roads and to integrate it smartly into the mobility system, with plans to have them ready as early as 2027 [30]. Currently it still holds that the road authority must approve of any test vehicle for it to be allowed to be tested on the road, where a legally liable driver must be present in the vehicle (source) regardless of the automation level being tested.

In private areas, the operations come under the site owner's responsibility and then regulatory obligations come from workplace safety law (*Arbeidsomstandighedenwet*) rather than traffic law. Machinery Directives in the Netherlands that govern safety conditions of machine operations are going to be replaced with Machinery Regulation that includes provisions for new developments such as artificial intelligence and cyber security (source). These and several other (CE marking, product liability, data protection) laws define safety conditions of machine operations but in the context of CAT, role definitions of 'operator', 'driver' and 'teleoperator' for example are not clear. The emerging ISO standard for automated operations, the 3691-4 gives a safety framework that sites can follow, but this is not backed up by legal regulations to do so. This also highlights the presence of overlapping yet loose standards, that sites need to interpret from ISO, workplace safety machinery laws, liability, insurance, etc., that requires significant expertise to tackle.

Port terminals often operate with a wide variety of heavy-duty machinery, mixed traffic and public interactions, so safety requirements have been high and expertise in certifications and legal liabilities are more prevalent. The port operator (e.g., APM Terminals, ECT, Kramer group) is legally responsible for ensuring a safe environment, the vehicle automation integrator (e.g., Terberg, Westwell) has product liability under the EU Product Liability Directives and certifies their vehicles for functional safety. In collaboration, the technology providers, port operator and insurance providers have shared liability agreements. The same overview also holds for automated yard operations.
However, when use cases involve some public road operations (e.g., crossing between yards with a public road) the ambiguity in regulations surrounding combined operations in road traffic law vs industrial area law causes hesitation regarding planning of future use cases that cross gates/public roads.

2.5 Challenges identified in literature and public sources

Building on the findings in Sections 2.1, 2.2, 2.3 and 2.4, the challenges hindering CAT implementations can be categorisedaccording to the three CAT4Yards building blocks: Vehicle & Control, Logistics & People, and Organisation.

These challenges are drawn from literature, public sources, and recent pilot deployments.

Vehicle & Control

- Robustness in adverse conditions: Sensor stacks struggle with rain, snow, and reflective surfaces, leading to false obstacle detection and emergency stops.
- Coupling automation: Trailer coupling remains a bottleneck, with robotic solutions still in early deployment stages. This is especially relevant for the Netherlands since standard trailers are often leased to numerous transport companies that cannot make changes to.
- Teleoperation scalability: Human fallback via teleoperation is common, but scaling this safely requires abstracted control interfaces and low-latency networks.
- Digital infrastructure limitations: Public networks (4G/5G/6G) and GPS devices are vulnerable to interference in metallic environments (e.g., ports), and multi-provider redundancy is often needed.
- Integration with TMS/YMS: Legacy systems often lack bidirectional communication, requiring custom middleware or broker systems for real-time coordination.

Logistics & People

- Process digitisation gaps: Many yards operate with undocumented, informal workflows. Digitisation is a prerequisite for automation but remains a major hurdle.
- Mixed traffic complexity: Autonomous vehicles in mixed environments face unpredictable human behaviour, requiring speed harmonisation and advanced V2X communication.
- Skill shortages and training gaps: Transitioning to CAT requires hybrid skillsets (telecom, automation, safety), but standardised training programs are lacking.
- Human-machine interaction: Teleoperators face cognitive overload due to poor interfaces and lack of depth cues. Safe abstractions for multi-vehicle supervision are still under development.
- Resistance and acceptance: Organisational inertia and union concerns about job losses hinder adoption. Demonstrations and inclusive planning are key to building trust.

Organisation

- Fragmented ownership and governance: CAT deployments often involve multiple stakeholders (OEMs, automation providers, site owners), leading to unclear responsibility and legal liability.
- Return on investment (ROI) uncertainty: High upfront costs and limited scalability in small deployments make ROI difficult to predict, especially without full supply chain integration. Results show that break-even points are only possible after scaling up.
- Infrastructure investment ambiguity: Lack of clarity on who funds physical and digital infrastructure upgrades slows down deployment.
- Regulatory bottlenecks: Legal permissions for public road operations are slow and complex, with national differences in approval processes.
- Standardisation gaps: Absence of common protocols for system integration, vehicle communication, and infrastructure design limits interoperability and scalability.

2.6 Integration of findings literature study

In the previous sections, detailed findings were presented for the various defined building blocks of the CAT ecosystem as shown in Figure 1.

In this paragraph, the focus shifts from individual findings toward an integrated perspective, in which the interconnections between sub-blocks within each building block are explored, with a view to linking insights across building blocks where relevant.

For each building block, (1) Vehicle and Control, (2) Logistics and People, (3) Organisation, and (4) Laws and Regulations, the findings for the corresponding sub-blocks are analysed to identify dependencies, synergies, and potential bottlenecks. For instance, within Vehicle and Control, the relationships between vehicle types, control tower capabilities, and physical and digital infrastructure are examined to understand how decisions in one domain influence requirements and constraints in the others.

The aim by taking this approach is to provide a clear system-level understanding of CAT deployment. The analysis provides not only the individual performance and feasibility of each sub-block but also the way in which choices and limitations influence outcomes across the building blocks.

2.6.1 Vehicle & Control integration overview

Following the general overview of building blocks and sub-blocks, the Vehicle and Control building block is first discussed to explore the interconnections between its sub-blocks: Vehicle Types, Control Tower, Physical Infrastructure, and Digital Infrastructure.

The four sub-building blocks can be conceptualized as a four-layer system architecture in which information, control, and operational readiness are discussed:

1. **Vehicle (type) Autonomy Layer**: Executes transport tasks based on embedded perception, localization, and control algorithms.
2. **Control Tower / Fleet Orchestration Layer**: Monitors and coordinates vehicle operations, provides mission planning, safety supervision, and teleoperation.
3. **Digital Infrastructure Layer**: Enables connectivity, data exchange, and system interoperability between vehicles, control towers, and logistics management systems (e.g., YMS, TOS).
4. **Physical Infrastructure Layer**: Provides the physical environment, including roads, lanes, charging systems, and sensors required for safe vehicle navigation.

Each layer depends on the capabilities of the layer below and constrains its performance. For example, Level 4 autonomous trucks can only achieve full driver-out operation when supported by reliable digital communication networks and a physically structured environment with consistent perception cues.

Table 10 summarises the interdependencies between the four sub building blocks of the Vehicle & Control building block. It illustrates how each sub-block both influences and relies on the others, highlighting the interfaces that must be aligned for CAT operations.

Table 10: Vehicle & Control domain dependencies.

From/To	Vehicle	Control Tower	Digital infra.	Physical infra.
Vehicle		Requires mission interface telemetry link and teleoperation fallback	Relies on low-latency V2X communication and secure data exchange	Depends on clear lane geometry, localization beacons and charging access.
Control Tower	Supervises vehicle autonomy and safety fallback		Needs redundant networking and API with YMS/TOS	Requires ergonomic operator facilities and full site coverage
Digital infra.	Provides V2X communication and perception data sharing	Enables orchestration dashboards and digital twins		Needs edge devices, cameras and RSU connectivity
Physical infra.	Provides vehicle operating domain	Hosts sensors, antennas and control tower facilities	Enables sensor and network installations	

Table 11 presents a typology of representative CAT configurations, linking vehicle autonomy levels to control tower requirements, infrastructure needs, and feasibility considerations. Vehicle types are explicitly categorisedby their operational environment, distinguishing between public road vehicles (e.g., diesel or electric trucks, including autonomous variants) and private site vehicles (e.g., terminal tractors and trailer movers used in yards or ports). This distinction highlights how infrastructure and control requirements differ depending on where the vehicles operate and helps illustrate the dependencies and trade-offs associated with each configuration.

Table 11: CAT Configuration Typology.

Configuration	Vehicle Autonomy	Vehicle Types	Operational Environment	Control Tower role	Infra. Requirements	Feasibility & Trade-offs
A. Teleoperated Fleet	Diesel Tractor Electric terminal tractor Trailer mover	Diesel Tractor Electric terminal tractor Trailer mover	Private site (yard/port)	Continuous human supervision	High-bandwidth 5G/6G, camera coverage, segregated lanes	Low technological risk; high operational cost; limited scalability
B. Supervised Autonomy	L3 autonomy with teleop fallback	Autonomous diesel truck (basic), Autonomous electric terminal tractor cabin	Public road & Private site	Human monitors multiple vehicles; teleop on exceptions	Reliable private network, mapped yard, charging points	Balanced safety and cost; feasible for mixed-traffic yards
C. Fully Autonomous Fleet	L4 autonomy; driver-out	Autonomous diesel/electric truck (advanced), Autonomous electric terminal tractor no cabin	Public road & Private site	Human oversight only for exception handling	Smart yard design, digital twin integration, standardised APIs	High CAPEX; requires advanced digital and physical maturity
D. Hybrid Human-Automated Operation	Mix of manual and automated vehicles	Mix of diesel/electric trucks, cabbed/cab-less terminal tractors	Public road & Private site	Integrated scheduling and monitoring	Shared networks, adaptive control zones, robust safety barriers	Easiest retrofit path; enables gradual scaling

The CAT Configuration Typology illustrates several important insights regarding the interdependencies between vehicle autonomy, operational environment, and supporting infrastructure. One key observation is that the level of vehicle autonomy strongly influences both control tower requirements and the design of physical and digital infrastructure. Higher levels of autonomy, such as fully driverless trucks or cab-less terminal tractors, require advanced physical layouts, reliable low-latency communication networks, and sophisticated control tower oversight. For example, cab-less autonomous yard tractors rely on geo-fenced routes, robust V2X communication, and possibly digital twin integration to ensure safe operation.

The operational environment also plays a critical role in determining technology choice.

Public road vehicles, such as Aurora's autonomous trucks, must meet strict safety regulations and integrate with broader traffic management systems, while private site vehicles, like Outrider or Terberg terminal tractors, can operate in controlled environments that allow faster adoption and more flexible testing of automation technologies. This distinction affects both deployment speed and infrastructure requirements.

The typology further highlights the trade-offs between capital expenditure, operational complexity, and scalability. Teleoperated fleets require lower initial investment but incur higher operational costs due to the need for continuous human supervision.
Fully autonomous fleets offer greater scalability and reduced reliance on human labour over time but necessitate significant investment in physical and digital infrastructure.
Hybrid configurations, which combine human and automated operation, provide a practical pathway for gradual adoption, enabling organisations to test automation technologies while maintaining human oversight.

These findings show that vehicle type selection cannot be considered in isolation.
The autonomy level determines the extent of control tower involvement, the reliability requirements for digital infrastructure, and the extent of physical infrastructure modifications. For instance, deploying advanced autonomous trucks without sufficient private 5G coverage or mapped routes would create safety and operational risks.

2.6.2 Logistics & People integration overview

Building on the integrated approach used for Vehicle & Control, this section focuses on the Logistics & People building block. It examines two sub-blocks: Traffic Management and Tasks, Skills, and Commitment of People.

The Logistics & People building block is linked with the Vehicle & Control building block. The autonomy level of vehicles directly affects traffic management strategies and the roles, skills, and workload of personnel. For example, fully autonomous electric terminal tractors without a cab, as discussed in the Vehicle and Control block, require centralised traffic management systems with V2V/V2I communication to safely orchestrate vehicle movements. In these environments, personnel focus on high-level supervision, exception handling, and monitoring via the control tower rather than direct driving, reducing the need for human intervention in routine operations.

On the other hand, teleoperated or semi-autonomous vehicles, such as diesel terminal tractors or basic autonomous trucks, create a mixed-traffic scenario where automated and manual vehicles could interact. This setup requires human oversight through teleoperation or manual intervention, careful speed harmonisation, and clear signalling to possible human-driven vehicles. Workforce roles expand to include teleoperation, situational monitoring, and traffic conflict resolution. Therefore, vehicle type selection directly affects operational and human factors requirements.

Similarly, in public road deployments, such as Aurora's advanced autonomous trucks, traffic orchestration relies heavily on integration with TOS/YMS systems and digital infrastructure, but human oversight remains necessary in edge cases. In private yards, fully automated fleets, like Outrider's cab-less terminal tractors, use geofenced lanes and centralised ECS platforms to optimise traffic flow, therefore minimising the need for manual intervention.

Table 12 shows how vehicle type, autonomy, traffic management, workforce roles, and control/infrastructure are interdependent.

Table 12: Integrated Vehicle - People - Traffic Mapping table.

Vehicle Type / Autonomy	Operational Environment	Traffic Management Approach	Workforce Role & Skills	Infrastructure / Control Requirements	Key Dependencies & Trade-offs
Diesel / Electric Terminal Tractor (Teleoperated)	Private site (yard)	Mixed traffic with teleoperation	Teleoperator for direct control, situational monitoring	Cameras, sensors, high-bandwidth network, basic ECS	Human workload high; low CAPEX; slower throughput
Autonomous Electric Terminal Tractor (Cab)	Private site (yard)	Supervised autonomy, centralised ECS, conflict resolution algorithms	Supervision, exception handling, teleoperation as backup	Geofenced lanes, V2V/V2I, digital twin, control tower	Medium CAPEX; moderate operational complexity; requires skilled personnel
Autonomous Electric Terminal Tractor (No Cab)	Private site (yard)	Fully autonomous, centralised ECS, V2V/V2I, optimised routing	High-level monitoring, fleet orchestration	Geofenced lanes, advanced ECS, V2V/V2I, high-reliability network, control tower	High CAPEX; reduced human labour; high digital and physical infrastructure needs
Autonomous Diesel / Electric Truck (Advanced)	Public road	Supervised hub-to-hub with TOS/YMS integration, limited teleoperation	Monitoring, exception management, freight orchestration	Roadside infrastructure, TOS/YMS integration, V2X communication, control tower	High CAPEX; regulatory and safety constraints; teleoperation needed in edge cases
Diesel / Electric Truck (Manual / L0)	Public road	Standard traffic management, human-driven	Traditional driver roles	Standard road infrastructure	Minimal CAPEX; no digital or control tower requirements; no scalability for automation

Table 12 summarises the interconnections between vehicle autonomy, traffic management strategies, and workforce roles within CAT operations. It highlights how the selection of specific vehicle types and autonomy levels directly affects traffic orchestration, operational procedures, and the skills required from personnel.

2.6.3 Organisation integration overview

The Organisation building block addresses the critical aspect of responsibility and ownership, or governance, within CAT operations. The introduction of autonomous vehicles and associated traffic and workforce management systems creates a complex web of shared responsibilities among site owners, technology providers, regulators, and labour organisations. As highlighted by surveys and research, investment in CAT technology is rarely isolated. It often involves service providers offering subscription-based solutions, joint infrastructure projects, and integrated digital and control systems. This collaborative model, while enabling rapid technology adoption, can fragment responsibility, particularly for safety, operational performance, workforce training, and infrastructure maintenance.

Effective governance is therefore essential to ensure that Vehicle and Control and Logistics and People systems operate safely and efficiently. For example, the deployment of fully autonomous, cab-less terminal tractors or advanced hub-to-hub trucks, as discussed in the Vehicle and Control block, requires clear assignment of responsibility for system monitoring, teleoperation oversight, and emergency intervention. Similarly, traffic management strategies and workforce roles within the Logistics and People block depend on governance structures that define accountability for training, operational decision-making, and supervision. Without shared governance and transparent responsibilities, conflicts may arise over who maintains physical infrastructure, who monitors system performance, or who ensures compliance with safety protocols.

Table 13 illustrates how governance and responsibility aspects in CAT operations are linked to specific vehicle types, control systems, traffic management strategies, and workforce roles.

Table 13: Organisation - Responsibility & Ownership Mapping table.

Governance Aspect	Relevant Vehicle & Control Elements	Relevant Logistics & People Elements	Key Implications / Dependencies
Joint Attribution of Responsibility	Oversight of autonomous vehicle fleets (e.g., cab-less terminal tractors, advanced trucks) and control tower operations	Coordination of teleoperators, fleet supervision, traffic management in mixed or fully automated yards	Shared governance needed between site owners, technology providers, and regulators to avoid conflicts and ensure safety
Transparency & Metrics	Monitoring vehicle performance, incident reporting, and ECS/TOS outputs	Tracking traffic flows, operator workload, and human-machine interaction efficiency	Requires standardised KPIs and data-sharing protocols to build trust and improve operational decision-making
Regulation & Legal Liability	Vehicle certification, compliance with safety standards (ISO 3691-4, VDI 2510), teleoperation protocols	Workforce safety, training compliance, traffic management rules	Clear legal definitions of responsibility reduce risk and enable deployment of new CAT technologies
Infrastructure Investment Responsibility	Physical infrastructure for CAT (charging, sensors, geofencing, network, edge computing)	Traffic management systems, control towers, sensor deployment in yards	Funding and maintenance must be clearly assigned to avoid delays and operational gaps
Accountability for Workforce Training	Operators and teleoperators of autonomous vehicles	Supervisors and personnel managing traffic flow and exceptions	Ensures sufficient skills for safe operation and adoption of new technologies, requires coordination with unions and HR

As shown in Table 13, joint attribution of responsibility ensures that oversight of autonomous vehicles, control tower operations, and traffic management is clearly assigned across site owners, technology providers, and regulators. Transparency and metrics link directly to the performance of autonomous fleets and human operators, providing the data needed to optimise vehicle movements, teleoperation, and workforce efficiency. Legal and regulatory clarity affects both vehicle certification and personnel safety protocols, while defined responsibilities for infrastructure investment and workforce training enable scalable, safe, and reliable operations.

2.6.4 Law & Regulations integration overview

The fourth building block, Laws & Regulations, defines the boundaries within which all other components of Connected and Automated Transport (CAT) must operate. While the technological, operational, and organisational building blocks determine what is possible, the regulatory framework dictates where and how these systems can legally function.

A key distinction exists between operations on private industrial sites and those involving public roads. On private property, CAT deployments fall under workplace and machinery safety law (e.g., the Dutch Arbeidsomstandighedenwet and the EU Machinery Directive), allowing greater flexibility but also placing full legal responsibility on site owners. In contrast, operations on public roads are bound by national traffic law, which currently requires the presence of a legally responsible driver during autonomous vehicle testing. The Netherlands is shaping these frameworks, with plans for a national legal structure for automated transport by 2027.

These legal boundaries directly influence how the Vehicle and Control systems are configured, for example, whether cab-less AGVs can be used or whether teleoperation is required and shape the Logistics and People building block by defining which traffic management and workforce practices are legally acceptable. Similarly, the Organisation domain depends on clear liability allocation between site owners, technology providers, and insurers. Table 14 summarises these relationships, showing how regulatory conditions influence decisions across the technical, human, and governance domains.

Table 14: Interrelations between Laws & Regulations and other building blocks.

Regulatory Aspect	Vehicle & Control dependencies	Logistics & People dependencies	Organisational Dependencies	Key Implications
Operational Jurisdiction (Private vs Public Roads)	Defines whether fully autonomous or teleoperated vehicles can be deployed; private roads allow flexibility under workplace law, while public roads require driver presence.	Determines permissible traffic management models; mixed-traffic scenarios may require speed limits and manual supervision.	Assigns liability and safety responsibility to site owners or road authorities.	Limits scalability of cross-boundary CAT operations and complicates routing between sites.
Machinery Regulation & CE Certification	Vehicle integrators (e.g., Terberg, Westwell) must ensure functional safety, cybersecurity, and compliance with new AI provisions.	Requires trained staff for inspection, maintenance, and certification audits.	Responsibility shared between manufacturer and operator under EU Product Liability rules.	Adds cost and delays to technology deployment; ensures safety baseline.
Liability & Insurance Frameworks	Product failures (vehicle malfunction) vs operational failures (traffic incident) must be legally distinguishable.	Teleoperators and supervisors must have clearly defined accountability; currently lacking standard definitions.	Legal liability distributed among site owner, technology provider, and insurer via shared agreements.	Unclear boundaries may slow down deployment and complicate incident investigation.
Workplace Safety Legislation	Defines physical segregation, warning systems, and speed thresholds.	Governs interaction between human workers and CAT vehicles (e.g., in mixed zones).	Site owner legally responsible for compliance and workforce protection.	Influences layout and operating speeds; shapes workforce safety procedures.
Emerging EU Frameworks for AI and Data	Affects autonomous decision-making and V2X data use; requires data transparency and explainability.	Requires new digital and data management competencies.	Demands compliance oversight and transparent reporting mechanisms.	Encourages ethical AI use but adds administrative complexity.

2.7 Conclusions

The analysis of the four building blocks, Vehicle and Control, Logistics and People, Organisation, and Laws and Regulations, highlights that CAT is not a single technological upgrade but an integrated system requiring alignment between technical innovation, human capability, governance, and legal certainty. The Vehicle and Control domains define the operational potential through vehicle autonomy, control tower design, and supporting infrastructure, while Logistics and People determine how these systems interact in dynamic environments and what new skillsets are needed to manage them safely. The Organisation building block establishes the framework of accountability and shared responsibility necessary to sustain multi-stakeholder cooperation, ensuring that technological and human systems are governed transparently and equitably. Finally, Laws and Regulations set the external boundaries that either enable or constrain deployment from private-yard automation governed by workplace safety law to European frameworks that will shape public-road interoperability.

Taken together, these building blocks show that successful CAT deployment depends on systems-level coherence. Therefore, gaps in one domain such as unclear liability, insufficient network coverage, or untrained personnel, can undermine the feasibility of the entire system. Therefore, the path toward scalable and safe CAT implementation lies in integrating these domains through iterative alignment. This is what can be seen in various pilots coming from the literature review. Only when the interplay between technology, people, organisation, and law is balanced can automated transport transition from isolated pilots and demonstrations to reliable, real-world operations.

3 Interviews

To obtain an overview of results from existing CAT projects, a selection of relevant projects is made. From these selected projects, we studied the project deliverables available and conducted interviews with project partners. The motivation for conducting interviews is twofold. Firstly, an interview allows for asking follow-up questions based on the published project results. Secondly, via an interview we could gather more sensitive information such as opinions of the project partners on bottlenecks for CAT and insight into less successful elements of a project.

We start in Section 3.1 with a discussion on the setup of these interviews and the methodology we used to analyse the data. In Section 3.2 we present the analysis of the interview results. We conclude and summarise our findings in Section 3.3.

As mentioned in Section 1.2, the literature review and the interviews were performed in parallel. Chapter 2 and 3 can therefore be read independently. In Section 4, we integrate the findings of both the literature review and the interviews.

3.1 Setup of interviews

We selected a total of eight relevant CAT projects that we included in our analysis. These projects are 5G-Blueprint, ANITA, AUTOSUP, AWARD, Living Lab Autonomous Transport Zeeland (LLATZ), MAGPIE, MODI, and SAVED. The selection criteria for relevant projects focused on the CAT topic, specifically how CAT was implemented, tested, or developed within each project. Additional criteria were the project's link to CAT4Yards, in particular whether its outcomes were relevant to CAT4Yards' goals, as well as ensuring a balanced mix of application-oriented developments and pilot activities. Table 15 presents an overview of the interviews conducted. Unfortunately, we were unable to interview a project partner of the AWARD project, as the project is still being executed.

Table 15: Overview of conducted interviews.

Project	Date interview	Interviewee
5G-Blueprint	April 30, 2025	Wim Vandenberghe (Agentschap Wegen en Verkeer)
ANITA	April 3, 2025	Prof. Dr. Christian T. Haas (Fresenius University of Applied Sciences)
AUTOSUP	April 25, 2025	Dirk Staelens (Vlaams innovatie-platform logistiek)
AWARD	--	--
Living Lab Autonomous Transport Zeeland (LLATZ)	May 9, 2025	Jennifer Vermaas (Solid Port Solutions)
MAGPIE	February 7, 2025	Geert Verhaeg (TNO)
MODI	February 7, 2025	Geert Verhaeg (TNO)
SAVED	June 25, 2025	Lejo Buning (HAN)

We used semi-structured interviews with an interview protocol as a guideline. This protocol has been validated in a test interview and can be found in Appendix A: Interview Protocol. It includes questions on project characteristics, project results, bottlenecks, and implementation. Depending on the interview, the protocol was closely followed, or the interview had a more free format. We agreed with the respondents that we would anonymise their personal opinions, but that project results could be shared under the corresponding project names.

In the analysis of the interviews, we used the building blocks presented in Section 1.2 as theoretical framework. The building blocks are divided into four sections: Vehicle and control, Logistics and people, Organisation, Laws and regulations. We added a final section on the impact of CAT. We linked the topics addressed in the interviews to these building blocks and investigated whether other relevant topics were mentioned by the respondents.

3.2 Analysis interview results

We will now discuss the interview results to present relevant insights from the corresponding projects. We structure the discussion of the interview results along the following four themes: Vehicle and control, Logistics and people, Laws and regulations and Impact of CAT. We refer to Section 3.3 for an explanation of the reason why there is no section on Organisation, which is part of the building blocks.

3.2.1 Vehicle and control

Vehicle

The vehicle characteristics of autonomous vehicles were discussed in only a few interviews. These include only the interviews on projects in which actual vehicle development and testing took place which are 5G-Bleuprint, ANITA and LLATZ. Topics addressed were mainly the technical challenges such as robustness of object detection in all weather conditions and smooth integration of the CAT vehicle in the flow of the operation. For more details on the state-of-the-art on vehicle development and technology, we refer to Section 2 of this report.

In the selected projects, autonomous vehicles were developed in close cooperation between multiple companies. For example, the autonomous terminal tractor developed in the LLATZ project was the result of a combination between an OEM (Terberg) and an automation kit supplier (EasyMile). The latter installed the LIDARS and sensors on the vehicle and was responsible for the software. This setup makes it possible for a single vehicle manufacturer to experiment in projects with different automation kit suppliers.

Whether the use of LIDARS and sensors was challenging differed per project. In the ANITA project, the vehicle and its technology were not the biggest challenges but more the integration into the logistics processes. The pilots in the LLATZ project revealed several technological challenges. Firstly, the vehicle was not always able to integrate smoothly into the existing operation. The driving speed was relatively low: in the pilots the average speed of the autonomous vehicle was around 25% lower than that of the regular manned vehicle. Moreover, when the autonomous vehicle detected an obstacle, it could brake very suddenly, which hindered upcoming vehicles. A second challenge was driving in extreme weather conditions such as heavy rain or snow. Particularly when the road was very wet, reflection could result in detection of non-existent obstacles.

Coordination and control

Autonomous vehicles require some type of control, for example via tele-operation or remote control in edge cases. The topic of control was extensively covered in the interview on the 5G Blueprint project. This project focused on 5G as an enabling technology for tele-operated vehicles in logistics. Five different use cases were studied, ranging from automated docking to platooning and tele-operated yard equipment. The project also investigated seamless tele-operation at border crossings.

The results of the 5G Blueprint project show multiple areas of application for remote control. Firstly, tele-operation in combination with autonomous driving is expected to be the way forward. Vehicles can autonomously drive or sail on predictable paths, and the remote operator can take over when the situation becomes more complex. Secondly, even when autonomous driving is not possible, tele-operation can be a solution for vehicles driving in hazardous or dangerous environments. Finally, tele-operation can have business potential in applications with high volatility in demand. For example, when a sea vessel with containers arrives at a port, there is great demand for transport to unload the vessel. In such a case, the availability of remote operators who can help unload containers in a short period of time can increase the business potential of the port.

Apart from remote control, there can also be situations where manual takeover is needed. For example, in the LLATZ project the autonomous terminal tractor followed a predefined path with a predefined number of deviation options. When the vehicle detected an obstacle, it could not deviate from these predefined routes to manoeuvre around a small obstacle. In those cases, an operator had to take over the wheel or remove the obstacle, such that the predefined path could be followed.

Digital infrastructure

To enable autonomous driving solutions or tele-operation, adequate digital infrastructure is required. The 5G Blueprint project investigated the benefits of 5G connectivity for tele-operated transport and experimented with different settings. The topic of digital infrastructure was therefore also an important topic in the interview on this project. The project concluded that a 5G network can provide a better connection than 4G, but that the connection quality can be seriously influenced by the environment. For example, the ubiquity of metal obstacles in a port environment with large container vessels can disturb the connection. In addition, a 5G network remains vulnerable to power failures or power outages. As a result, the requirement of ultra-reliability is difficult to guarantee with only one 5G network. The project therefore experimented with multi-provider connectivity and demonstrated the large added value of parallel networks and multiple SIM-cards. The project also found that a 5G network is not always needed. In different tests, they were able to perform the same manoeuvres on a 4G network, although the image quality was better with 5G. The pilots showed that 4G seems mainly suitable for teleoperation of barges in a quiet environment and without crossing borders. The latency for 4G and 5G was comparable in tests with teleoperated barging, but 5G had improved video quality which enhanced the overall experience and improved safety in ports with heavy barge traffic. In a cross-border setting, teleoperated driving with 4G resulted in handover latency above the acceptable threshold and 5G was needed to safely switch providers when crossing the border. For yard solutions, even a Wi-Fi network could be sufficient. But for end-to-end tele-operation on the long haul 5G connectivity is crucial, which makes this application unlikely, given the extensive 5G network needed. A final challenge identified in the 5G Blueprint project was that the core features of 5G stand-alone, such as network slicing or uplink priority, were not yet available from vendors. Therefore, a custom core had to be developed to carry out the tests.

CAT-solutions on yards do not only rely on the available connectivity network but also depend on the digital infrastructure on the yard itself. The available digital infrastructure can be a bottleneck for the progress of a project. In the ANITA project, some of the yard systems could not receive messages, which required workaround solutions for real-time communication. Changes in the digital infrastructure were not possible, but enabling bidirectional communication or supporting real-time adjustments could have streamlined integration and significantly improved performance. The ANITA project also emphasised the need for standardised machine communication protocols and logic. The lack of standardisation in digital communication was identified as one of the key hurdles for full automation.

Physical infrastructure

The requirements on the physical infrastructure to enable CAT implementation were not extensively covered in the interviews. Both the ANITA project and the LLATZ project used vehicle technology that did not require changes to the physical infrastructure. Other projects did not or not yet conduct actual pilots and had therefore limited insights into the role of the physical infrastructure.

The differences in physical infrastructure between public roads and private terrain can also play a role for CAT. One respondent argues that CAT-solutions for hub-to-hub operations could be challenging, because the public road can bring unexpected situations, such as roadblocks or road closures. From that perspective, yard implementations are easier.

Autonomous vehicles perceive their surroundings via sensors and cameras. In addition, they are often equipped with a digital map of the area where they drive. In the LLATZ project, the automation kit provider would first manually drive the route with the autonomous vehicle to create a digital map. Based on this map, the vehicle could then navigate autonomously. Comparing the information from the sensors with the map also allows the vehicle to detect objects. In the LLATZ project, the vehicle could not deviate from the given route, so it would stop once an obstacle is detected. This demonstrates the importance of good quality maps for the smooth operation of such vehicles. At the same time, the advantage of this technology is that changes to the physical infrastructure, such as beacons in the road, are not needed. Comparable technology was used in the ANITA project, where no changes to the physical infrastructure were necessary either.

To achieve easier implementation of autonomous vehicles, technology can be used to allow vehicle-to-infrastructure communication. In the interview on the MODI and MAGPIE project it was stated that this technology will likely be developed for CAT-implementations on the public road, but that yard applications could also benefit from it.

Coordination with TMS/FMS

Implementation of CAT requires coordination with existing systems such as Terminal Management Systems (TMS), Terminal Operating Systems (TOS), or Fleet Management Systems (FMS). System coordination and integration was extensively discussed in the interviews on the ANITA project and the SAVED project. Whereas terminal operations are usually quite standardised, these projects identified that yards often lack digitalisation and standardisation. Some yard systems are outdated. For example, administration, task assigning or planning is still done by hand and/or on paper. This makes automated transport on yards or between yards very challenging.

One of the challenges in the ANITA project was the integration of the systems of two yards. Despite their proximity and shared ownership, both yards had incompatible, independent systems. These systems could only send messages but not receive them.

Workaround solutions were therefore required to enable real-time communication. The project developed a so-called *broker system* to translate and manage communication between systems. Contract-specific language from finance was used to model processes as contracts, and the steps were first digitally verified before they were executed to increase reliability. The SAVED project also identified connecting to the IT systems of the logistics companies as one of the biggest challenges for CAT-implementation. This requires a certain level of digital maturity in the companies which is not always there yet. The project investigates data exchange on a multimodal level, where data on the location and load of the container is exchanged between partners in the supply chain. The vehicle itself also needs to be included in the process of exchanging data, since the vehicle both generates and requires information. The vehicle can for example share its location with the shipper but also needs information on pick-up location of the load. Finally, also in the interview with project partners from the MODI and MAGPIE projects system integration was mentioned as a bottleneck. The respondent explained that separate components or systems are often present, but that they have to be connected by means of software to achieve integration.

The interviews showed two solution types for system integration. The common approach is to connect various systems and let them communicate with each other, for example, via APIs. The broker system developed in the ANITA project is an example of this approach. An alternative solution is to use one new overarching system that integrates the various tasks. In the interview on the ANITA project the business potential was identified for new companies developing such a system. Another respondent expressed the expectation that such a party will enter the market within a few years and that the development and implementation of CAT will then gain momentum. He sees it as an important task for knowledge institutions to prepare for this transition.

The integration of systems is challenging not only because of a lack of digitisation but also because of a lack of standards in communication protocols or digital infrastructure. When every yard uses different systems, the implementation and integration of autonomous vehicles cannot be easily standardised and often requires a case-specific approach.

3.2.2 Logistics and people

Integration in logistics work processes

The integration of autonomous vehicles in current logistics work processes was discussed very extensively in almost all interviews. The most important topic was the challenge to understand and map out current processes, which is a crucial requirement before autonomous vehicles can be successfully integrated. Mapping out current processes can be challenging, because processes are often complex, undocumented, and rely on implicit knowledge. One respondent explains that the information flow in the yard was difficult to outline, as there was a lot of unwritten communication between workers who shouted instructions to each other or communicated non-verbally. Understanding processes is even more challenging when the transport between multiple yards is investigated, and each yard has a different form of yard management and different levels of digitisation. This was confirmed by the ANITA project that focused on yard-to-yard operations. They expressed that mapping out processes was more cumbersome and time-consuming than expected. The LLATZ project found that digitising processes is crucial for autonomous transport. One-on-one replacement of a manned vehicle with an autonomous vehicle will not work. First, all processes in the yard must be delineated, digitised, and aligned. Although this can be challenging, the results of several projects also show that a lot of efficiency can already be gained by digitising and optimising processes without transitioning to full automation.

For example, the ANITA project developed a simulation model to analyse the effects of a drive-thru process with digitalised check-in and truck paperwork. They showed that performance could be improved by 15-20% by optimising processes. Other respondents also mention digitising business processes as the first step that can be taken with high expected benefits and relatively low investment costs. Implementing such changes in your logistic processes brings benefits today and enables a smoother integration of CAT in the future.

In the interviews, we discussed the challenges and bottlenecks for the implementation of CAT-vehicles. The main bottleneck identified by the SAVED project is the integration of autonomous vehicles into the logistics processes. This integration includes assignment of tasks to the vehicle, data-exchange between systems and adjustments in the processes. One of the key insights of the ANITA project was that automation was not so much blocked by technology or costs, but more by deeply embedded workflows and organisational inertia. The results showed that the implementation of CAT required many changes in the way of working and a shift from human intuition to explicit rule-based instructions. The LLATZ project mainly identified bottlenecks of CAT implementation in functional details, such as the inability to autonomously (de)couple, the complex port environment with mobile harbour cranes, and the influence of weather conditions on object detection. The project also identified the need for a fleet management system that includes all assets: otherwise, the impact of autonomous vehicles will be limited to pilot studies. The ANITA project also demonstrated the need for integration with other vehicle types in the yard, such as cranes and reach stackers. To achieve integration, discussions are needed with manufacturers of these vehicle types to reach a common understanding of communication between vehicles. In relation to this, standards or protocols have to be developed for machine communication to facilitate vehicle-to-system communication and vehicle-to-vehicle communication.

Integration into logistics processes also includes integration at the supply chain level. The AUTOSUP project develops digital support systems for automation of the entire supply chain. The project is motivated by the fact that many automated systems lack chain integration. As a result, the return on investment of these automated systems is limited because they cause bottlenecks later in the chain where processes are not yet automated. The respondent illustrated this effect with an example from the port of Antwerp. In this port, the container terminals are located mainly on the left bank of the river, and the train terminal on the right bank. Containers can be transported from the right bank to the left bank by truck or rail. One could invest in extending train capacity, possibly also in combination with autonomous trains. This would result in higher container volumes at the terminal. When you consider the supply chain perspective, you find that you also need additional (autonomous) crane capacity on the terminal side to unload containers from the train. Otherwise, containers are waiting to be unloaded, which brings associated safety risks. The importance of including the perspective of the entire supply chain was also discussed in the interview on the SAVED project. The respondent illustrated this with the following example. Suppose an autonomous system can guarantee that containers arrive to a certain location without involvement of personnel. Then you might need additional security measures or handling to take care of these containers. These examples shows that the supply chain perspective is needed to avoid the propagation of bottlenecks through the supply chain.

Traffic management

The topic of traffic management was only discussed to a limited extend, probably because the projects that performed actual pilot studies only did so with a single vehicle. Hence, managing a fleet of autonomous vehicles was outside the scope.

The only topic related to traffic management that came up in the interviews was the smooth integration of a CAT vehicle into the traffic flow on the yard.

The interviews on the SAVED project and the LLATZ project highlighted the importance of traffic management to ensure a smooth and safe integration of autonomous vehicles in mixed traffic environments. The interview on the SAVED project identified that driving autonomously can be challenging, but that responding to the traffic situation at hand is at least as complex. This particularly holds for mixed traffic situations and on the public road. The pilots conducted in the LLATZ project also showed that integrating smoothly in the traffic flow was sometimes challenging. After detecting an obstacle, the autonomous vehicle could break abruptly, hindering the flow of upcoming vehicles. In addition, the vehicle driving speed was quite low, which affected the traffic flow. Finally, the pilot route included a roundabout. The autonomous vehicle was programmed so that it only entered the roundabout when there was enough space. With the busy traffic on the terminal, the autonomous vehicle sometimes waited a long time before entering the roundabout. Due to these reasons, the project had to conclude that with the current status of technology, the autonomous vehicle could not keep up with the required efficiency on the terminal.

To improve traffic flow, several solutions could be considered. An option is to adjust the physical infrastructure by creating separate lanes for autonomous vehicles or installing traffic lights. None of the projects included in our analysis incorporated such solutions. They all tried to implement CAT within the existing physical environment. The LLATZ project considered several modifications to the vehicle to improve traffic flow. Examples are specific lighting on the vehicle to inform other road users of its status and the vehicle honking when changing lanes. A final solution is to implement a traffic management system. Such a system could include, amongst others, the resolution of traffic conflict, speed harmonisation, and priority of vehicles. In the LLATZ project, a fleet management system (FMS) was implemented which gave the vehicle its jobs. The vehicle then followed a programmed route from A to B. Once an obstacle was detected, the vehicle gave a warning to the FMS. The FMS in the LLATZ pilot only included a single autonomous vehicle. To fully benefit from an FMS, ideally, all vehicles on the terminal or yard would be included in the system. This requires complete digitisation of the terminal or yard, which can be challenging in mixed-traffic environments and environments with external drivers.

Tasks, skills and commitment of people

Autonomous transport solutions are systems that partly or fully take over the tasks of the driver. They therefore have a great effect on the personnel. The human component in relation to CAT was brought up in many interviews. Respondents mentioned the advantage of needing less personnel due to automation as well as the required flexibility of personnel for successful implementation of CAT.

The fact that automation requires fewer drivers can be a solution to the driver shortage faced by many logistics companies. In the 5G Blueprint project, both autonomous driving and autonomous sailing were studied. Whereas vehicles on the road often have a single driver, a vessel operates with a crew. Autonomous solutions for vessels enable a so-called 'crew-reduced' mode where less people are needed to operate the vessel. Such solutions directly bring economic benefits without having to remove all the people from the vessel.

Jobs will not only disappear because of automation, but new jobs will also arise, and existing jobs will change. These new jobs require personnel with the right training and knowledge of digitisation and automation. A successful shift to full autonomy therefore also requires a shift in mindset, not just in vehicles or systems. The results of the ANITA project show that this is not always easy.

The project proposed various changes in the logistics processes and developed simulation tools to validate their impact. Although the simulation results were very good, they were not used by the terminal operators. These operators could not see the potential of the new tools, as they were used to their way of working and lacked a complete overview of the processes. This demonstrates that the commitment of the people involved is crucial to fully benefit from the potential of CAT-solutions.

The 5G Blueprint project focused on tele-operation, which clearly changes the driver's job. Instead of being physically present in the vehicle, the driver can control the vehicle from an office. As a result, driving in dangerous environments might no longer be necessary. When tele-operation on the long-haul would be possible, the work conditions of international truck drivers would change substantially. They can now stay in the office, which might attract other personnel. The LLATZ project also gave an example of changes that were required in the jobs of other employees who work alongside the autonomous vehicle. The vehicle in the LLATZ project transported containers which could be loaded onto the chassis by a reach stacker. These reach stackers operate completely manually. To inform the driver of the reach stacker that the autonomous vehicle was ready to receive its container, a light was installed on top of the vehicle indicating its status. When the light turned green, the vehicle was ready for (un)loading a container. Such changes in procedures also require the proper instruction of all personnel.

3.2.3 Laws and regulations

Public road

CAT has multiple legal aspects. One important aspect is the legal permission required to drive on public roads, which was discussed in a few interviews. Apart from the ANITA project, the other projects which planned to experiment with CAT on public roads did not succeed in getting permission. The interviewee of the LLATZ project explained that on private terrain you need to comply with machine regulations. But when you enter the public road, you face automotive regulations. In several interviews, the Experimenteerwet was mentioned, an extension to the Dutch law for road traffic that would enable experimenting with automated systems in motor vehicles. Both the LLATZ project and the 5G Blueprint project commented on the long time it takes to request permission for experiments on the public road via the Experimenteerwet. The 5G Blueprint project encountered similar problems with the Belgian Gelijkwaardigheidstoelating. As a result, neither project experimented with driving on public roads. The 5G Blueprint project decided to rent the Lommel Proving Ground, a test track owned by Ford with more than 100 km of road. Experiments were conducted on these tracks to increase confidence in the technology and to speed up innovations. Surprisingly, the ANITA project did not face any difficulties in obtaining permission to use a public road between two yards in Germany. In the end, however, autonomous operations were carried out mainly within the terminals and not on public roads. But this was due to the performance of the whole system, more than to legal restrictions. The SAVED project does not intend to experiment on the public road but does analyse the steps that would be required to do so. Together with the road authorities, (local) governments and terrain owners the partners that are needed in this process are identified and necessary steps are outlined for the trajectory towards permission to drive on the public road.

Safety

Many interviewees also emphasised the importance of safety in relation to CAT-solutions, although most of them just stressed the importance without further elaboration.

Only the interviews on the 5G Blueprint project and the LLATZ project discussed safety more concretely.

In the LLATZ project, considerable time was invested in preparing the safety case for the pilots. In this safety case, all possible risks were identified, and mitigation measures were proposed. In the end, the remaining risk had to be at an acceptable level before experiments could be conducted. Per project and per terminal or yard such a safety case has to be made. In the interview on the 5G Blueprint project, several mitigating measures were discussed. These include, among others, educating people who work in the vicinity of autonomous vehicles and instructing them, for example, on where walking is not allowed. Safety concerns can also limit changes to the current situation. In the ANITA project, for example, it was not possible to change infrastructure, because of safety reasons and compliance and rules within the companies.

Although autonomous vehicles might pose additional safety challenges, their introduction can also increase safety. This was illustrated in one of the use cases of the 5G-Blueprint project which demonstrated a tele-operated bobcat transporting bulk powdered material in warehouses or inside ships. Both the environment and the material pose safety risks to the driver. Positioning the driver in an environment where the vehicle can be controlled via tele-operation results in increased safety, better ergonomics, and better continuity.

Acceptance

We asked most of the interviewees if they would expect resistance in society because of the loss of jobs for low-skilled personnel due to yard automation. Since societal acceptance was outside the scope of the projects, respondents shared their personal opinions. Some did not expect much resistance, since automation would also create new jobs. Others agreed with the statement that new jobs would be created but still expected some level of resistance. They argued that part of this resistance could be prevented by involving people in the process. The LLATZ project gave an example of a way to increase the acceptance of autonomous technology. This project was closed with a demonstration in which project partners were taken on a bus tour over the terminal. During this tour they saw the autonomous vehicle in action. Such demonstrations create trust by showing the working technology in practice. Therefore, more long-term practical pilots are essential. In the AUTOSUP project, it was recognised that the majority of companies adopt a wait-and-see approach related to CAT-solutions. They are considering organising an automation event in the port of Antwerp-Bruges. This event could be used to inform visitors about the available technology for autonomous driving and sailing. They particularly would like to focus on automation for transport applications, since autonomy for warehousing is well known by most companies.

3.2.4 Impact of CAT

Economic impact

CAT is expected to have an impact on several dimensions. Particularly the economic impact was extensively discussed in all interviews. Most projects investigate the economic impact in terms of efficiency gains, costs, or required investments. The possibility of spreading the workload more evenly over time and the fact that fewer personnel is needed were also mentioned as positive economic impacts.

The expected increase in efficiency (i.e. higher throughput, reduced downtime, improved reliability) is mentioned in one of the interviews as the unique selling point of automation.

In combination with good planning, automation can result in so-called ‘peak-shaving’: a more evenly distributed workload over time. Other respondents also mention that CAT can reduce workload peaks, particularly due to the stable continuous operation that can be achieved. Enhanced continuity can thus be seen as an advantage of CAT, although flexibility might decrease. When the workload is highly noncontinuous, for example caused by seasonality patterns or by high peaks in workload resulting from the arrival of a sea vessel that has to be unloaded quickly, CAT is less flexible than human drivers. A possible solution in those situations is to temporarily increase the fleet size of autonomous vehicles, although too many autonomous vehicles on a limited area can hinder a smooth flow of operations. The interview on the 5G Blueprint project also pointed to hiring additional external tele-operators who can drive vehicles remotely as a solution for peaks in demand.

One of the key insights of the ANITA project was that even small digital improvements can lead to big performance gains. The project used multi-agent simulations and digital twins to show that digitising processes such as check-in and truck paperwork can result in a performance increase of 15-20%. Not all projects found a positive impact on efficiency. In the LLATZ project, efficiency was also an important metric. The terminal where the pilots took place decided not to continue with CAT for the moment because the efficiency of the vehicle was too low. More technical developments were needed before the autonomous vehicle could integrate smoothly into existing operations. The results of the different use cases of the 5G Blueprint project demonstrate that CAT-solutions on the yard are expected to result in the fastest returns. On the yard you do not need permission for the public road. Moreover, from a technological perspective, the yard is less complex, and you directly profit from increased efficiency, increased safety, and possibly reduced damage costs. Particularly applications such as automated docking and tele-operated yard vehicles are seen as low hanging fruit. The AUTOSUP project also investigates the impact on efficiency but takes the efficiency of the total supply chain into account. With the digital decision support system developed in the project, users can evaluate different automation technologies and directly see their impact on efficiency and sustainability.

One of the outcomes of the SAVED project is that companies do see the potential of CAT, but that the return on investment is still low. As a result, the practical applicability of CAT seems limited despite the technological possibilities, which is also found in other projects. High investment costs are mentioned as a possible reason for this. Implementing CAT not only involves investing in new vehicles, but investments are also needed for digital infrastructure, software adjustments and possible changes to logistics processes. CAT implementations in small scale projects, with only a limited number of vehicles, are therefore less likely to be economically attractive. The SAVED project considers such small settings to be more useful as innovation lab than for actual implementation. One of the use cases studied in the SAVED project is a relatively small operation on a business park in the northeast of the Netherlands. Because the number of container movements per day is limited, a high-tech solution is not directly necessary. Nevertheless, the companies involved are interested in identifying requirements for CAT and its possible impacts. They are willing to learn about these new technologies to prepare for growth possibilities in the future. The digital twin that is developed in the SAVED projects helps them to ease deployment of CAT vehicles on the business park.

The differences in economic impact observed by the various projects lead to the question whether solutions are generalisable. One respondent argues that 90-95% of yard operations are similar and that there is thus a high potential for the generalisation of solutions. Another respondent pointed out that the real added value of yard automation can often only be seen after implementation.

This makes a priori calculations on the return on investment complicated. This problem is expected to decrease over time, as more examples of implementations are available and experience grows.

The reduced need for personnel is an important driver for efficiency gains. The different use cases in the 5G Blueprint project also demonstrate that there is most business potential when personnel reductions can be achieved. For example, the business case for platooning is very limited when the second truck still needs a driver. There is a small advantage of the reduction in fuel consumption resulting from the aerodynamic effects of the short distance between the trucks in the platoon. However, this benefit is reduced on highway networks with many entrances and exits, such as the network in the Netherlands, where the distance between trucks must be larger to allow other vehicles to safely merge onto the highway. The 5G Blueprint project mainly sees business potential for platooning in combination with teleoperation and automation. In that case, the tele-operator can drive the vehicle to the highway and connect it to a platoon. On the highway, only the first vehicle in the platoon needs to be controlled by a tele-operator; the others can follow autonomously. When a vehicle in the platoon reaches its destination exit, the tele-operator takes over and brings the vehicle from the highway to its destination. Such a scenario results in personnel reduction but is not expected to become reality soon. In the short term autonomous or tele-operated sailing is expected to be profitable more than driving, since vessels can operate in so-called 'crew-reduced mode'.

Environmental impact

Most CAT vehicles are equipped with an electric driveline that has a positive environmental impact. In only one of the interviews, this environmental impact was addressed. This seems to indicate that environmental benefits are not the main motivation for considering CAT. The AUTOSUP project investigates impact in a broad sense, including the effect of emission reduction. One of the use cases in this project is, for example, related to the transport of containers to a container repair terminal in the port of Antwerp. This transport is currently carried out by diesel trucks. The project analyses the economic and environmental impact of replacing this vehicle with an autonomous electric truck.

Societal impact

Next to economic and environmental impact, CAT also has an impact on society. Some of the statements in the interview protocol asked for the opinion of respondents on societal resistance to autonomous vehicles and their expectation on the timeline for the implementation of CAT.

In discussing the impact of CAT on employment, one respondent named the driver shortage the main driving force of automation. Several respondents expected that societal resistance resulting from job losses would be limited and could be managed by taking employees along in the process towards automation.

Secondly, the speed with which CAT will be implemented also affects society. Most of the respondents do not expect many CAT-implementations on yards in the next 10 years. But they do expect to see several large distribution centres starting with automation in 5 to 10 years. The respondents agreed on an expected phased rollout of CAT, beginning with implementations on yards and followed by short trips on public roads in industrial areas. Only after that will they foresee CAT-implementations on the public road, first nationally and then also internationally.

The highway was mentioned as one of the first public road domains where automated driving could be possible. One respondent mentions that there might be a dependency between yard implementations and the technology for CAT on public roads. He argues that the business case for yard automation could depend on technologies such as vehicle-to-vehicle communication and infrastructure-to-vehicle communication, which are often developed for CAT on public roads.

3.3 Conclusions

We analysed the interviews and structured the comments of the respondents according to the building blocks. The building blocks are divided into four sections, but we found that the topics in the section 'Organisation' were not mentioned by the respondents. This section covers aspects around responsibility, ownership and organisation of autonomous vehicles. We think that is caused by the scope of the selected projects, which focused more on the technological developments and logistical integration and not so much on the legal and business aspects of CAT. Moreover, autonomous vehicles are still in an early development phase and that these aspects might come into the picture in a later stage. There are also a few topics that are extensively mentioned in the interviews. This holds for the topics of integration into logistics work processes and coordination with TMS/FMS. Other topics, such as vehicle technology and physical infrastructure were mentioned only to a very limited extend. In addition to the topics covered in the building blocks, there was a lot of attention for the impact of CAT in the interviews, particularly for the economic impact. We therefore added a separate section in our interview analysis on this.

When we summarise the analysis of the interviews, we can identify some common topics in all the projects. Firstly, many respondents mention the importance of mapping and digitising processes. Only those projects without real-life tests did not address this. When processes are highly digitised and there is a well-functioning yard management system, integrating autonomous vehicles is considered to be easier. The results also indicate that optimising and digitising processes can already bring substantial benefits, even without moving to automation. This insight can therefore be a motivation for companies to start investing in digitising and optimising processes now, because this will reduce the additional investments needed for automation in the future.

A second common topic is the need for standardisation in several areas. Firstly, standardised processes on yards enable smooth integration and generalisability of CAT-solutions. Secondly, the value of standardised communication protocols was mentioned to enable system integration and vehicle-to-vehicle communication. Finally, standardising physical infrastructure on yards and aligning with the infrastructure on public roads can enhance CAT-applications between yards where short distances on public roads have to be covered.

The final topic that appeared in most interviews is that the human factor is crucial to the success of CAT. Although the need for personnel might decrease with automation, commitment of personnel will be needed to fully benefit from the advantages of CAT. To avoid resistance among personnel or in society, informing and instructing people is therefore necessary. The latter is also crucial to ensure a safe working environment in which people and machines work together.

4 Conclusions – CAT SOTA

The goal of Work Package 1 (WP1) within the CAT4Yards project was to provide a clear State of The Art (SoTA) overview of Connected and Automated Transport (CAT) technologies and their associated implementation conditions. This knowledge base serves as the foundation for the Impact Assessment Tool being developed in WP2, which aims to quantify the effects of CAT integration in different operational environments. WP1 sought to identify the current status, bottlenecks, and key enabling factors across the four main CAT integration building blocks, **Vehicle & Control**, **Logistics & People**, **Organisation**, and **Laws & Regulations**, while also capturing practical insights from ongoing pilot projects and industry experts through targeted interviews.

4.1 Overview of Findings Across the Building Blocks

Vehicle & Control

The Vehicle and Control building block defines the technological and operational backbone of CAT. Findings show that vehicle autonomy levels, control tower functionality, and supporting infrastructure are highly interdependent. Automated yard tractors, AGVs, and mixed-traffic vehicles increasingly rely on advanced perception systems, high-definition localization, and robust fleet orchestration layers. However, achieving scalable deployment requires matching developments in physical infrastructure (private 5G/6G connectivity, geofenced layouts, charging systems) and digital infrastructure (integration with TOS/YMS, standardised data used in APIs, and real-time data exchange). Control towers are evolving into human-in-the-loop orchestration centres combining automation scheduling, exception handling, and teleoperation capabilities. Yet, limitations in operator scalability, video latency, and standardisation of system interfaces remain key challenges. The analysis highlights that investments in one domain, such as high-level autonomy, also requires advances in the others. For example, deploying cab-less automated trucks requires high network redundancy, resilient fleet orchestration, and updated safety governance procedures.

Logistics & People

The Logistics and People building block focuses on how CAT interacts with human operations and traffic systems within yards and terminals. Two central aspects emerged: traffic management and tasks, skills, and commitment of people.
In fully automated environments, centralised control systems (e.g., Konecranes TEAMS ECS or Outrider Mission Control) manage routing, conflict resolution, and scheduling through sophisticated algorithms and V2X communication. In mixed-traffic contexts, safety and coordination depend on speed harmonisation, multimodal sensing, and clear communication between automated and manual vehicles. Teleoperation is often used as a transitional solution bridging manual oversight with automated driving.

The human factor remains crucial since automation shifts the workforce from driving to supervision, exception management, and system integration roles. However, skills gaps, operator cognitive overload, and training deficits were identified as barriers to scaling operations.

The success of CAT depends not only on technology readiness but also on human adaptation and commitment. This reinforces the link to the Vehicle & Control findings: advanced automation requires both resilient digital systems and skilled human operators to ensure safe and reliable operations.

Organisation
The Organisation building block governs the framework of responsibility, ownership, and accountability within CAT implementations. The findings highlight fragmented responsibility between site owners, technology providers, and regulatory authorities as a key challenge. Shared governance and transparent performance metrics are essential to prevent operational disputes and ensure oversight.
Infrastructure investment responsibilities, particularly regarding physical installations, edge computing, and network maintenance, are often unclear, leading to project delays. Furthermore, the absence of clear accountability for workforce training slows organisational adaptation.

This building block directly connects to both Vehicle & Control and Logistics & People: technology providers depend on site owners for infrastructure, while operators and teleoperators depend on organisational policies for training and safety governance. Establishing joint responsibility models and standardised governance frameworks is therefore a requirement for scalable CAT deployment.

Laws & Regulations
The Laws and Regulations building block defines the legal framework that enables (or constraints) CAT deployment. A distinction is made between private industrial areas, governed primarily by workplace safety and machinery law, and public roads, regulated by national traffic law. Within private areas, owners have more flexibility to deploy autonomous vehicles under occupational health and safety regulations, while on public roads, testing still requires a legally responsible driver. The Netherlands is at the forefront of developing a harmonised European framework, with full regulatory integration for automated transport expected by 2027.

Legal uncertainties persist around liability, certification, and data management. Overlapping standards (ISO 3691-4, Machinery Regulation, CE marking, and EU AI Act) require site operators to interpret and combine multiple legal instruments. This affects decisions across the other building blocks: Vehicle & Control configurations depend on the legal approval of automation levels; Logistics & People must adapt traffic management and training practices to comply with safety law and Organisation must formalize liability and insurance arrangements. In short, regulatory clarity is the foundation upon which safe, transparent, and economically viable CAT operations can be built.

4.2 Insights from Stakeholder Interviews

The interviews conducted with stakeholders from ongoing CAT projects complement the SoTA analysis by providing real-world validation of the identified challenges and opportunities. Three recurring themes emerged:

1. **Digitisation as a precursor to automation:**
   Many respondents emphasised that automation can only succeed when processes are well-digitised. A robust Yard Management System (YMS) and clear data flows greatly simplify CAT integration. Even before automation, process digitisation itself brings significant operational benefits, motivating early investment.

2. **Need for standardisation:**
   Stakeholders consistently called for standardised processes, communication protocols, and physical infrastructure to enable interoperability between systems and vendors. Standardisation also supports cross-site scalability and interoperability between private yards and public road segments.
3. **Human commitment and societal acceptance:**
   The transition to automation does not eliminate the human factor. Personnel involvement, training, and transparent communication are essential for safety, acceptance, and long-term success. Addressing worker concerns and promoting awareness were highlighted as critical for sustainable adoption.

These insights reinforce the building block relationships identified in the SoTA. Standardised digital interfaces support vehicle orchestration, while early process digitisation supports data-driven traffic management and operational transparency. Likewise, human engagement aligns directly with the *Logistics & People* and *Organisation* findings, automation succeeds only when governance and workforce development progress in parallel with technology.

4.3 Synthesis and Implications for WP2 and the CAT4Yards Project

The combined analysis of literature and stakeholder insights confirms that the maturity of CAT systems cannot be assessed solely through technology readiness. True readiness depends on the systemic coherence across all four building blocks. The Vehicle & Control domains provide the technological capability; Logistics & People define the operational interface; Organisation provides governance and accountability; and Laws & Regulations establish the external enablers.

For the WP2 Impact Assessment Tool, this means that the parameters influencing CAT feasibility and impact must be interconnected rather than isolated. For instance, the selection of a vehicle autonomy level should automatically reflect requirements for digital connectivity, control tower capability, workforce training, and legal compliance. The insights gathered in WP1 will therefore inform WP2 by providing the technical and operational baselines, as well as the boundary conditions for realistic CAT deployment scenarios in the upcoming use cases (DPD, Elopak-Verbrugge, and QTerminals Kramer).

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Appendix A: Interview Protocol

The interview protocol consists of two parts. Part 1 includes several statements that could be used to start the conversation. Part 2 contains the questions on the project and project results.

Part 1 – Statements

1. Within 10 years, the number of fully automated yards will not significantly increase.
2. Substantial social resistance is to be expected because of the loss of jobs for low-skilled personnel due to yard automation.
3. Mixed traffic yard applications will only be rolled out when autonomous driving is introduced on public roads.
4. Yard automation for mixed traffic will never be a success; It is too expensive, and safety cannot be adequately guaranteed.
5. It will be more difficult to deal with peak loads when automation solutions are implemented.

Part 2 – Questions

1. Can you give a short description of the project?
   a. Project name
   b. Which technologies are investigated or developed?
   c. What is the focus of the project?
   d. Which hardware is investigated (if applicable)? (vehicle types, sensors, etc.)
   e. To what extent did the project also include infrastructure? (physical / digital infrastructure)
   f. Which application was studied? (public road/yards, day/night, inside/outdoors)
   g. What was the traffic situation in the use case(s) of the project? (mixed traffic, traffic rules, how is traffic on the yard managed)
2. Can you give an indication of the costs related to the CAT-implementation studied in your project?
   a. Vehicles: price, how many?
   b. Infrastructural changes: road design, control room, etc.
   c. Safety
3. What were the main results of the project?
   a. What do you see as 'quick wins', results that can be implemented in the short term (within 5 years)?
   b. Which results do you expect to be implemented in the middle long term (5-10 years)?
4. How can the project results be implemented in practice? Which steps need to be taken and are certain adjustments required?
5. What are the bottlenecks that you encountered during the project?

   - Technical / Legal / Safety / Financial (investments, ROI) / Social (acceptance, level of education, job security)
6. Are there other insights obtained during or after the project that would be useful for us to include?
7. What is your personal opinion on possible reasons that can hinder the implementation of CAT?

Appendix B: Operational Costs

Cost analyses are subject to assumptions and uncertainties regarding economic policies, battery developments, automated driving system costs, etc. The costs and performance related to remote driving support are still uncertain [15]. Table 16 provides estimates for cost factors relative to manual driven equivalents.

Table 16: CAT implementation cost factors, sourced from [6]

Factor	Autonomous Diesel Vehicle Basic	Autonomous Electric Vehicle Basic	Autonomous Diesel Vehicle Advanced	Autonomous Electric Vehicle Advanced	Comments
Tax	Same	Same [6]	Same [6]	Same [6]	
Depreciation period					Highly uncertain. Higher utilization period, so could be less than baseline.
Depreciation factor					Expected to depreciate faster
Variable maintenance	+25% [6]	+25% [6]	0% [6]	0% [6]	
Fixed maintenance	+25% [6]	+25% [6]	0% [6]	0% [6]	
Energy usage	Same [6]	Same [6]	-10% [6]	-10% [6]	
Energy usage stationary	Same [6]	Same [6]	Same [6]	Same	
Variable energy cost	Same	Same	Same	Same	
Euro vignette					Could be lower due to better fuel economy, but depends on emission class
Rest time factor					
Insurance factor	Same [6]	Same [6]	-10% [6]	-10% [6]	
Interest rate					

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