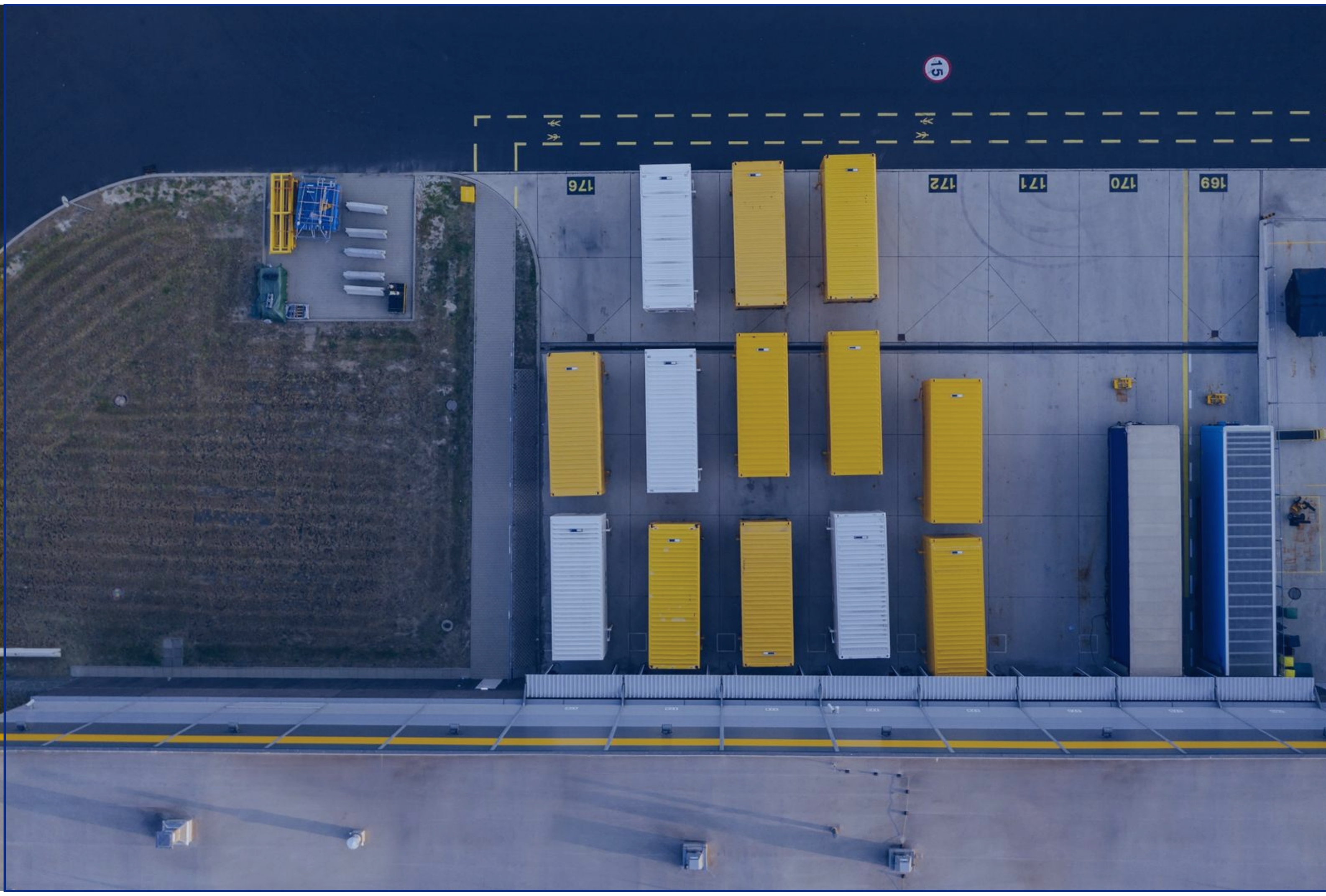
Connected Automated Transport at Yards: requirements and impacts for logistics



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Connected Automated Transport at Yards: requirements and impacts for logistics

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OEM

Public

Legal organization

Knowledge organizations

Supporting organizations

Summary

Connected Automated Transport (CAT) holds potential for logistics companies to reduce costs, lower emissions and mitigate driver shortages. However, many logistics organizations hesitate to take first steps because requirements, impacts and efforts of implementation are not sufficiently clear, while OEMs are reluctant to invest without clear market demand. The CAT4Yards project addresses this gap by developing and validating a structured approach that creates insight into CAT requirements and ex-ante impacts, enabling logistics organizations and OEMs to take the next steps.

This report describes the further development of the *Logistics Centred Design Approach Connected Automated Transport*, specifically for yards as this is a controllable application area for first implementation of CAT. The approach builds on the CAT4Yards state of the art analysis, based on literature review and expert interviews. It follows an iterative, stepwise design process carried out in three structured workshop sessions, covering definition, implementation and validation of designing a CAT concept.

Two tools support this process:

- The **CAT Requirements Database**, which helps to evaluate alternatives and align the requirements into a CAT design, grouped by building blocks on four levels: **vehicle & control**, **logistics & people**, **organization**, and **laws & regulation.**
- The **Ex-ante Impact Assessment Tool**, which quantitatively and qualitatively assesses CAT impacts on **total cost of ownership, efficiency, personnel, sustainability, safety, flexibility,** and **implementation effort**.

These tools enable developing CAT designs, and comparing these with current manned operations, performing what-if analyses, and identifying the key cost drivers and sensitivities that most strongly influence outcomes.

The approach was developed and further validated in three logistics use cases, each with distinct characteristics, ensuring the method's applicability beyond the CAT4Yards use cases.

From these use cases, four central lessons emerged:

- **Coordination and control** is a key building block for integration CAT at yards.
- **Process standardization**, **digitization** and **task redesign** are prerequisites for integrating CAT into logistics operations.
- **Understanding cost drivers through sensitivity analysis** strengthens strategic decisions.
- **Comparing multiple CAT designs** helps organizations identify practical starting points and define a **realistic transition path** toward the desired end state.

For the three use-case partners, the method provided: clear understanding of requirements and boundary conditions to support internal decision-making, concrete input for discussions with OEMs and suppliers, and confirmation that while transition phases may temporarily challenge TCO, final CAT designs can be favourable for long-term logistics performance.

As such, **the approach opens the discussion with stakeholders in what way Connected Automated Transport can improve their operations and the next steps for implementation**.

Future research will refine the approach as amongst others technology and cost estimates evolve. Also, the aim is to extend it beyond yard operations to industrial zones and hub-to-hub transport and apply it to the preparation of real-world CAT trials. To conclude, this makes our approach an important step on the path towards a safe, efficient, and sustainable transport system enabled by Connected Automated Transport.

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Abbreviations

ADS	Autonomous Driving System
CAT	Connected Automated Transport
ESC	Electronic Stability Control
ESP	Electronic Stability Programme
FMS	Fleet Management System
KPI	Key Performance Indicator
OD	Origin-Destination
ODD	Operational Design Domain
OEM	Original Equipment Manufacturer
TCO	Total Cost of Ownership
TMS	Transportation Management System
V2C	Vehicle to Cloud communication
V2I	Vehicle to Infrastructure communication
V2N	Vehicle to Network communication
V2V	Vehicle to Vehicle communication
V2X	Vehicle to Everything communication
YMS	Yard Management System

1 Introduction

1.1 Connected Automated Transport potential solution for challenges transport sector

The freight transport sector faces multiple challenges regarding sustainability, safety and efficiency. The European Union set targets for reducing emissions and traffic fatalities. Furthermore, it is expected that transport volumes will continue to grow while there is also a growing driver shortage [1].

Connected Automated Transport (CAT) has been gaining interest as a promising innovation to address these challenges [2, 3]. CAT refers to transport systems with progressively higher levels of automation. It is linked to the broader category of Connected, Cooperative, Automated Mobility (CCAM), which also covers passenger transport innovations. CAT is expected to enhance efficiency, safety, and sustainability in transport while helping to address driver shortages.

1.2 Uncertainties hinder development and uptake of Connected Automated Transport

Stakeholders – such as transport companies, shippers, port authorities – in CAT-projects in the Netherlands (a.o. Living Lab CATALYST, MODI) recognize the expected benefits and see the need to take the next steps towards deployment of Connected Automated Transport. The sector wants to prepare and execute real-world experiments that not only cover testing technical functionality of autonomous vehicles but especially focus on integration of these vehicles in logistics operations. Before implementation at scale can happen, the impact of the use of these vehicles on businesses and their operations, and consequences for people, both drivers and other road users, should be understood.

However, several uncertainties hinder stakeholders taking next steps towards deployment. Logistics companies face uncertainties about the efforts, requirements, and impacts of integrating autonomous vehicles into their operations. As a result, even those willing to conduct real-world trials often hesitate to act. Alternatively, Original Equipment Manufacturers (OEMs) are hesitant to invest when logistics companies do not show clear commitment to deploy autonomous vehicles, resulting in an uncertain demand for CAT from the market. So, for both logistics companies and OEMs, there is a need to reduce uncertainties to enhance development and uptake of Connected Automated Transport.

1.3 Aim: identifying efforts and impacts of integrating CAT at yards

Given the above, we established the CAT4Yards project, a public-private partnership, consisting of logistics organizations (DPD, Elopak, Verbrugge, DHL Global Forwarding), OEMs (Terberg and consulting company Solid Port Solutions), knowledge organizations (HAN University of Applied Sciences, HZ University of Applied Sciences, TNO), provinces (Smartwayz, Provincie Noord-Brabant, Provincie Zeeland, Provincie Zuid-Holland), port authorities (North Sea Port, Port of Rotterdam, SmartPort), legal organization (ITL Attorneys) and supporting public authorities (Ministry of Infrastructure and Water Management, Rijkswaterstaat). Together, the CAT4Yards project partners aim to:

Develop an integrative approach to identify efforts and the associated impacts of integrating Connected Automated Transport at yards

This approach should guide transport companies that have limited knowledge of Connected Automated Transport in taking the first steps that ultimately lead to implementation of CAT at their yard. We focus on yards as we expect that this will be the first Operational Design Domain (ODD) for CAT implementation in the Netherlands. Yards – restricted areas such as (air)port terminals, factories, or business parks – are less complex than public roads in terms of traffic situations and interaction with other (vulnerable) road users. Since obtaining approval for CAT deployment on public roads remains challenging in the Netherlands, logistics companies favour taking first steps in yard environments.

Ultimately, we envision that this approach can (and should) be extended to industrial zones and long-haul transport corridors, which is beyond the scope of the CAT4Yards project.

1.4 Outline of the report

This report presents the findings of the CAT4Yards project. Chapter 2 outlines the steps taken to develop our integrative approach. Chapters 3 and 4 detail its key components: the conceptual framework of CAT building blocks and the impact assessment. In Chapter 5, we combine these elements into the *Logistics Centered Design Approach for Connected Automated Transport* and illustrate its application through an example use case. Finally, Chapter 6 provides lessons learned and Chapter 7 provides an outlook on future steps.

2 Approach and method development

At the time the project started, there was no off-the-shelf methodology available to assess the efforts and impacts of CAT to yard operations. Therefore, we developed a methodology for which we adopted a design thinking approach [4, 5]. In parallel to the CAT4Yards project, the EU-funded MODI project was established and, in that project, a first round of the design steps depicted in Figure 2.1 was followed. First steps were taken to develop a 0.1 version of the methodology [6]. In CAT4Yards we built further, by making a few more iterations (a.o. additional literature review, expert interviews and evaluation in logistics use cases) on the steps of the design cycle and make further improvements and refinements as compared to the 0.1 version developed in the MODI project: *The Logistics Centred Design Approach CAT*.

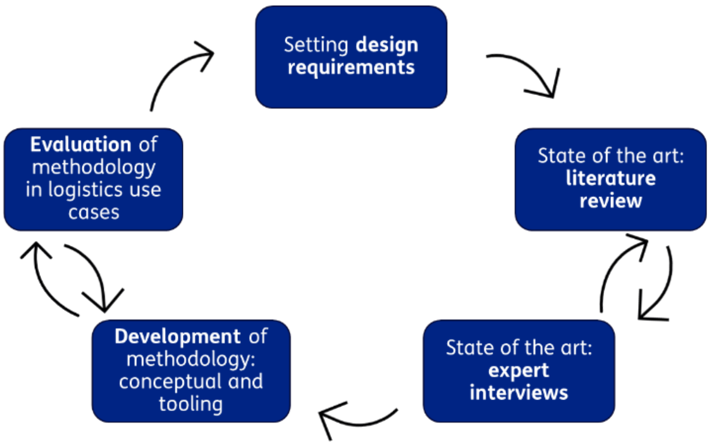


Figure 2.1: Iterative design process in MODI and CAT4Yards, adapted from [5].

An important design requirement for our methodology is the ability to evaluate 'what-if' scenarios for different CAT designs at yards. The methodology should be generic and applicable to use cases beyond those used for its development and (initial) validation. Additionally, assumptions should be made explicit, and input values should be able to be adjusted easily as knowledge of CAT evolves. The methodology should support the analysis of various CAT scenarios within logistics contexts, accommodating both quantitative and qualitative inputs and outputs.

Version 0.1 of the Logistics Centred Design approach contains [6, 7]:

- A conceptual model of the 'CAT building blocks' – key elements describing the main categories of requirements for integrating Connected Automated Transport into logistics. These categories can be grouped into vehicle and control, logistics and people, organization, and laws and regulations.
- The CAT requirements database as a supporting tool for the 'CAT building blocks'.
- Ex-ante impact assessment tooling to assess the impact of implementing a CAT design with respect to Total Cost of Ownership (TCO).
- An iterative, step-by-step process to apply these tools to a logistics use case.

- Validated the step-by-step process and the supporting tooling (database and ex-ante impact assessment) in a logistics use case (Drayage operation: ~5 km. transport from container stack at container yard to warehouse outside of the yard).

Version 0.1 of the methodology provided a solid basis for assessing CAT integration requirements and estimating TCO prior to CAT implementation. As highlighted in the initial methodology report [7], the approach can be strengthened by updating the CAT building blocks to incorporate new (technological) insights, broadening the assessment beyond TCO to account for wider non-financial impacts, and validating the methodology in additional use cases to improve its generalizability.

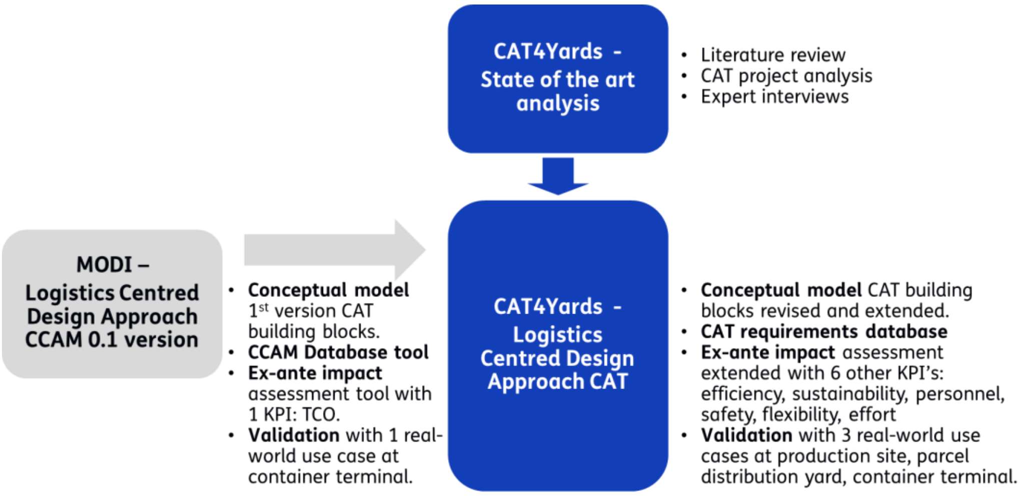


Figure 2.2: Inputs and outputs of CAT4Yards project: Logistics Centred Design Approach Connected Automated Transport.

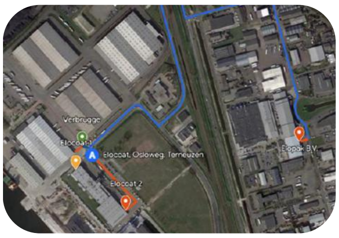
In this report we describe version 0.2 of the Logistics Centred Design Approach CAT (see

Figure 2.2). We incorporated the Cat4Yards state-of-the-art analysis that consisted of literature review and expert interviews [8]. Based on the state-of-the-art analysis, we extended and revised the conceptual model of the CAT building blocks of v0.1 and adapted the CAT requirements database tool accordingly – see Chapter 3.

- We extended the ex-ante impact assessment tool with 6 additional KPI's: efficiency, sustainability, personnel, safety, flexibility, effort of implementation – see Chapter 4.
- We formulated interview – and workshop formats to enrichen the iterative process of the Logistics Centred Design Approach – see Chapter 5.

We validated the above in three logistics use cases, detailed in company-specific reports. Each use case has distinct characteristics and boundary conditions (see Figure 2.3), all of which are incorporated into the Logistics Centred Design Approach.

DPD Oirschot -
Shunting swap bodies at distribution yard



Elopak-Verbrugge -
Shunting raw and processed materials between warehouse and production site

Terberg -
Shunting containers between container terminal and warehouse in mixed-traffic

Figure 2.3: Logistics Centred Design Approach validated in three use cases.

3 Building blocks integrating CAT in logistics practice

3.1 Conceptual Framework

The CAT building blocks are key categories describing the requirements for integrating Connected Automated Transport into logistics. In the 0.1 version of the Logistics Centred Design Approach, the foundation was laid [7]. Through a state-of-the-art analysis in CAT4Yards, [8]– combining literature review and expert interviews - we expanded and refined the conceptual framework of the CAT building blocks (see Figure 3.1). We provide a description of the building blocks in section 3.3.

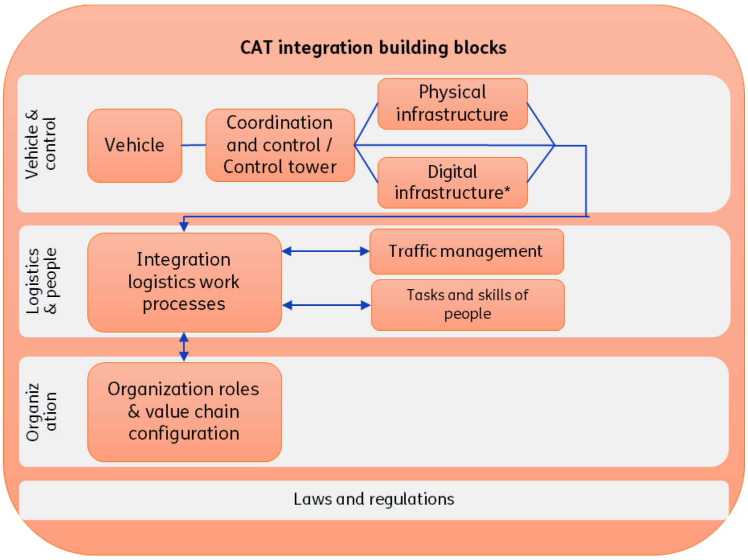


Figure 3.1: CAT building blocks for integration in logistics [6, 7].

We distinguish between four levels that group the building blocks into overarching categories:

- **Vehicle and control** – constitute of building blocks that describe the options and alternatives regarding the most technological aspects of a CAT design. It concerns the autonomous vehicle concept, the way it is controlled (coordination and control), and what physical and digital infrastructure is required to accommodate the autonomous driving of the vehicle.
- **Logistics and people** – constitute of building blocks that describe the options and alternatives regarding integration in logistics processes, traffic management (related to logistics processes) and the division of tasks between the autonomous vehicle and personnel that is responsible for other tasks than the driving task.
- **Organization** – consists of the building block that describes alternatives for organizational roles and value chain configuration. The different stakeholders in the value chain of developing autonomous trucks and executing autonomous transport can have different positions in creating and delivering value.

- **Laws and regulation** – this layer is not further specified in different building blocks as we consider the topic of regulation as an overarching/underlying boundary condition that facilitates the application of autonomous transport. Here, we do not identify alternatives or options but describe the legislation that is applicable to the context of CAT at yards.

In section 3.3 we describe the building blocks in more detail.

Selecting a specific option for each building block will result in a **CAT design** which describes the Connected Automated Transport concept that can be applied to a logistics yard use case. As one can imagine, these building blocks are not stand-alone requirements that must be met. To the contrary, there are a lot of interdependencies (see section 3.4). For example, when opting for a specific vehicle type without a cabin, this has implications for the type of (remote) coordination and control via a control tower and subsequently for the connectivity requirements for digital infrastructure, which in turn affects logistics processes and the division of tasks between autonomous vehicles, control tower and human operators.

To facilitate the development process of building a coherent and consistent CAT design (i.e. all building blocks are aligned and not contradicting one another), we developed the CAT requirements database as a supporting tool [7]. We summarize the most important aspects of this tool in section 3.2.

3.2 CAT building blocks requirements database

The database used called TypeDB is based on a PERA-model [9]. This stands for Polymorphic Entity Relation Attribute. The polymorphic part makes TypeDB, a very flexible database, as will be explained in this section.

- **Entities**
  - These are the building blocks as per section 3.1 (e.g. vehicle, digital infrastructure). Represent the key requirement categories in CAT designs
  - Can have sub-types (vehicle is the main entity, truck is a sub-type of a vehicle)
- **Relations**
  - Connects different entities to each other with roles
  - Main role is dependency, with the relation describing the cause and effect (e.g. the vehicle entity and control entity are linked: if the vehicle type has no cabin, then there is no driver; if there is no driver, then remote operation is required).
- **Attributes**
  - Enriches the entities with values. For example, cost or powertrain type are attributes of the vehicle entity.

The building blocks from Section 3.1 form the highest level of entity. These can have sub-entities (as explained in Section 3.3). For example, the vehicle building block is the main entity. A sub-entity of vehicle is ‘Powertrain’. The (sub-)entities have attributes attached to them.

This research applies two different roles in the database. First, the dependency role, with a cause-and-effect relation.

This relation describes which (sub-)entity triggers another entity within the same or a different building block. The second relation describes the requirements of a building block. Depending on the CAT design, an entity can become a necessity and therefore labelled '*Required*'. This means that the user should choose between one of the alternatives in the entity. Another option is that an Entity is labelled '*Optional'.* Then, it is not explicitly necessary to choose from the alternatives, but for a coherent design, it is better to do so. The relations are polymorphic in a way that the design of an entity does not state specifically that an entity always 'plays' the cause or effect role in the dependency relationship. The entities can take both roles. As well as that depending on the CAT design, it is not predetermined that an entity is *'Optional'* or *'Required'.* More on the interrelations is explained in Section 3.4.

Attributes form the last element of the database, which are attached to both entities or relations. The attributes are polymorphic as they can be shared with different entities and across different types, they can be values or text, either based on free input or by multiple choice.

The output can be retrieved from the database using queries. The following query returns all the vehicle entities. Due to the polymorphism, it also returns all sub-entities of the entity vehicle.

Query 1: Retrieving all vehicle entities.

```
match $x isa vehicle;

get $x;
```

Furthermore, it is possible to obtain all relations that are defined. For example, all dependencies/ relations are obtained with the following query:

Query 2: Retrieving all dependency relations.

```
match

      (cause: $y, effect: $z) isa dependency;

get $y, $z;
```

3.2.1 Usage of the CAT requirements database

The use of this database for CAT applications comes with an iterative process. Due to the extensive possibilities, it is not likely that all attributes attached to the entities will have a value in the first run. During the iterations, the database will return more entities that are labelled *'Required'*. Then it is up to the user to assign values to attributes related to the entities that are required. With the newly assigned values, a next run will determine new interrelations and assign new relations and values to other entities until eventually everything that is required to have a value in the considered CAT design, has a value.

The database returns the output in three tabular formats. The first describes the requirements, roles and relations of the entities. The second table presents the dependencies and roles of the entities, giving an overview of which entities cause the value (effect) of another entity. Lastly, it returns the attributes and attribute values which then can be used for further assessments, both quantitative and qualitative. In Appendix A, an example is presented for the input of the CAT requirements database as well as an example of the Attributes table that is provided by the database.

3.3 High-level description of building blocks

This section presents the individual building blocks, as introduced in section 2, building further on [7] and using the latest state-of-the art from [8]. It describes in more detail the scope of the building blocks, what is included and the choices that a logistics service provider can make in a CAT design.

3.3.1 Vehicle and control

The first building block relates to the **vehicle** and the vehicles-based elements that a logistics service provider can choose from. Firstly, one can choose from three different types of vehicles. A trailer mover, only used for shunting trailers small distances on a yard, a terminal tractor, mainly used on yards and industrial zones and lastly, a truck, used for long distances on public roads. The operational speeds are reflected in this as well: maximum trailer mover speed is 15km/h, maximum terminal tractor speed is 30 km/h and maximum truck speed is 80 km/h. From the use cases, the rule of thumb is used to use an average operational speed of 60% of the maximum speed for the vehicle types.

For the truck and terminal tractor, a choice must be made with regards to the autonomy level. This autonomy level describes the autonomous capabilities of the vehicle. For more complex operations, an advanced autonomy level might be required. Both the truck and terminal tractor can be chosen with or without cabin options. Furthermore, there are options with regards to the powertrain of the vehicle. For now, diesel and electric powertrains the options provided, but in future configurations, it can be possible that both biofuels and hydrogen become an option.

The automation technology is often provided by an automation provider and not solely by an OEM. If the vehicle automation technology is not provided with the vehicle, then a separate choice of provider is needed. Some suppliers allow for the vehicle automation provider to be changed during the vehicle lifespan. Other choices are permanent, although the value propositions are still in development. The automation hardware (sensors, lidars etc.) itself can be installed on only the vehicle, or both vehicle and trailer, resulting in more manoeuvrability, but higher costs. Lastly, in context of navigation, two options are proposed. In option 1 the vehicle determines its route with GPS and HD-maps. In option 2 the vehicle determines the route and suitable surface to drive on using installed cameras.

Table 3.1: Available options for the building block vehicle.

	Variable	Options
Vehicle	Vehicle type	➢ Truck ➢ Terminal tractor ➢ Trailer mover
	Cabin	➢ Yes ➢ No
	Powertrain	➢ Diesel ➢ Electric
Autonomy & automation	Autonomy level	➢ Basic ➢ Advanced
	Automation dependent tech-provider	➢ Included to vehicle ➢ Own fixed choice to vehicle ➢ Own flexible choice to vehicle
Automation hardware	Automation hardware	➢ None ➢ Only applied on vehicle ➢ Applied on vehicle & trailer
Navigation	Navigation	➢ GPS + HD maps ➢ Vehicle autonomously decides where to drive (using sensors)

Coordination and control

Autonomous vehicles require some form of remote assistance or remote control to monitor whether the vehicle is performing its tasks correctly or controlling the vehicle (in exceptional circumstances) remotely.

Here, we distinguish the following levels of remote operation:

1. Manned
2. Full route remote operation
3. Section-based remote operation
4. Situational remote operation
5. Exception-based remote operation

Control intensity decreases at higher levels, shifting from remote control to remote assistance, with fewer human interventions as shown in Figure 3.2. The appropriate level depends on the operational design domain and vehicle type.

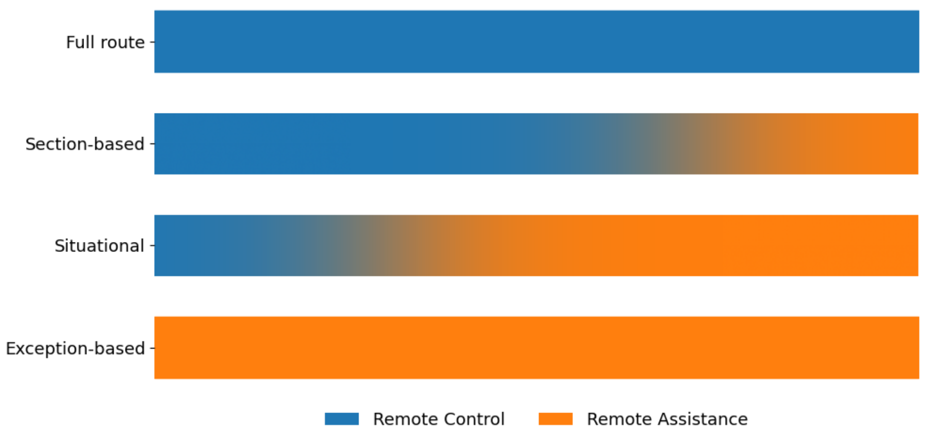


Figure 3.2: Main type of remote operation depends on the appropriate level of coordination and control.

In a standard logistics operation using manned vehicles, it requires one driver to control one vehicle. In autonomous operation, this can differ depending on choice of vehicle, level of autonomous coordination and operational domain. The following vehicle-to-operator ratio options are available by default and most likely: *1:1, 4:1, 8:1, 20:1***.** However, the user can apply other ratios if preferred.

Emergency scenarios still require human intervention, either through full remote recovery by an operator or by deploying a safety driver onsite.

For trip execution, vehicles may plan and follow their own routes based on a predefined origin (O) and destination (D) or select from one or more predefined options. This choice influences the required autonomous capabilities of the vehicle.

Table 3.2: Available options for the building block coordination and control.

	Variable	**Options**
Remote operation	Remote operator	➢ Manned ➢ Full route ➢ Section based ➢ Situational ➢ Exceptional
	Vehicle-to-operator ratio[1]	➢ 1:1 ➢ 4:1 ➢ 8:1 ➢ 20:1
Vehicle Operator	Driver	➢ Yes ➢ No
Navigation	Path planning	➢ OD with fixed route ➢ OD with alternative routes ➢ Only OD (vehicle flexibly plans its own path)
Safety	Fall back scenario	➢ Remote controller ➢ Safety driver in vehicle

Physical infrastructure

Yard layouts may need adaptation to vehicle capabilities. If not feasible, vehicles must meet higher performance requirements. Key modifications include automating gate entry/exit and automating handling at the dock or stack. Traffic flow can be managed through dedicated lanes or mixed traffic, with roundabouts and signals improving predictability. Operators may also install sensors and cameras, while remote operation requires a control room, either onsite or external.

Table 3.3: Available options for the building block Physical infrastructure.

	Variable	**Options**
Operational domain	Domain type	➢ Public ➢ Yard ➢ Industry
Terminal layout	Implement changes	➢ Yes ➢ No
Physical modifications to infrastructure	Gate option	➢ Automated ➢ Manned
	Route	➢ Dedicated lanes ➢ Mixed traffic

[1] These are the standard options, every other integer ratio x:1 is also possible.

Physical Control Room	Safety measures	➢ Traffic light ➢ None
	Sensor control	➢ Sensors on terminal ➢ None
	Dock/stack	➢ Automated ➢ Manned
	Location	➢ On site ➢ External
	Size	➢ Small ➢ Medium ➢ Large

Digital infrastructure
Digital infrastructure covers the entire digital ecosystem needed to instruct and enable the vehicle. It includes communications among vehicles and with other systems such as Transport Management Systems (TMS) and Yard Management Systems (YMS) or for access control. Cybersecurity and privacy are generally managed by connectivity providers and vehicles, though logistics parties may impose additional requirements. For yard operations, existing networks may suffice; in other domains or where coverage is inadequate, operators can choose public networks (4G, 5G, satellite) or private options (Wi-Fi, or dedicated 4G/5G). Vehicle communication supports multiple modes among others: vehicle-vehicle (V2V), vehicle-network (V2N), vehicle-infrastructure (V2I), vehicle-cloud (V2C) communication, collectively referred to as vehicle-everything communication (V2X). Choices in coordination and control, as well as the complexity of the yard will determine data to be exchanged and the necessary bandwidth and latency to guarantee quality of service.

Digital maturity of systems such as TMS and YMS must also be evaluated, as they need to allow for instruction and monitoring of autonomous vehicles. The level of adaptation and effort required for Integration with TMS / FMS / YMS depends on current system capabilities. Three maturity levels are defined: Mature, Partially Mature, and Not Mature.

Table 3.4: Available options for the building block Digital infrastructure.

	Variable	Options
Security	Security sufficiency	➢ Yes ➢ No
Connectivity	Network sufficiency	➢ Yes ➢ No
	Network type	➢ 4G ➢ 5G ➢ 6G ➢ Wi-Fi ➢ Satellite ➢ Other
	Network ownership	➢ Public ➢ Semi-public ➢ Private
Communication	Communication type	➢ V2V ➢ V2N ➢ V2I ➢ V2C ➢ V2X ➢ Not Applicable
Digital systems	Digital maturity	➢ Yes ➢ Partially ➢ No

3.3.2 Logistics and people

Integration logistics work processes
Shifting from manned to autonomous operation is complex, as there are different degrees of complexity of autonomous implementation and integration. This has an impact on the operation (route, speed, operational hours) and processes (docking, gate entry/exit, integration with transport order system and warehouse operations, mixed traffic).

Therefore, four different integration levels describe the impact on the operation and processes. The first level described a limited operation of autonomous vehicles for a specific part of the total operation with full-route control, limited speed and suitable routes. The impact on processes is therefore also limited. The second level has similar operating speed and routes compared to current operations. The impact on processes is moderate, and digitalisation and automation of processes is required. The third level opens the possibility to look beyond current operating hours and explores 24/7 operation. This has a high impact on other processes as these should also enable 24/7 operation. Level 4 proposes a redesign of the logistics operation for better optimization and collaboration of all related work processes at the yard, fully enabling autonomous transport.

Table 3.5: For the building block 'Integration logistics work processes' there is one choice to make, the level of integration. This table explains what these levels mean and what the impact is on the operation and on the processes.

Level of Integration	Impact on operation	Impact on processes
Level 0	Current, manned operation.	Current manual processes, no impact.
Level 1	Vehicle runs unmanned but with full-route remote control. Limited in speed, routes, and hours.	Minimal impact on processes, small adaptations to enable limited amount of autonomous transport (separated process)
Level 2	Unmanned operation with remote control only where needed. Speed, routes and hours are similar to current operation.	Moderate impact on processes, automation and digitalisation of current processes required
Level 3	Mostly autonomous operation with remote control only in specific situations. Enables continuous (24/7) operation.	High impact on processes, automation and digitalisation of current processes required as well as extending operational hours of processes
Level 4	Complete redesign: fully autonomous, continuous 24/7 operations	Complete digitalisation of systems. Redesign of processes to fully enable autonomous transport.

Traffic management
Yard operators can take several measures to improve traffic management. They may apply standard traffic rules or prioritize autonomous or manned vehicles, like public transport prioritization in residential areas. The level of interaction between traffic types is critical. Operators can permit or restrict interactions between manned and autonomous vehicles, as well as with vulnerable road users. In mixed-traffic situations – where manned and unmanned vehicles share the same road - additional enforcement measures may be introduced to ensure that drivers of manned vehicles comply with traffic rules.

Additionally, for more awareness, operators can install static visual warnings or require safety training and instructional videos before allowing human drivers access to areas with autonomous vehicles.

Table 3.6: Available options for the building block traffic management.

	Variable	Options
Traffic rules	Priority rules	➢ Standard traffic rules ➢ Autonomous vehicle has priority ➢ Other traffic has priority
Traffic interaction	Interactions allowed	➢ Yes ➢ No
	Diversity of traffic participants	➢ Homogeneity ➢ Heterogeneity
Handling chaotic situations	Increased enforcement	➢ Yes ➢ No
Informing road users	Information type	➢ No additional information ➢ Static Visual warnings ➢ Safety training

Tasks and skills
Autonomous driving transforms the distribution of tasks within operations. Responsibilities traditionally handled by drivers must be reassigned to other personnel, such as remote operators, monitors, or warehouse staff, or automated entirely. Key processes affected include driving, (un)loading, and (de)coupling. Additionally, we distinguish the planning tasks that concerns planning the yard transport movements and related communication. This can be executed by a human operator, or it can be digitalized and automated. Consequently, the role of a human planner shifts to a more supervising and monitoring task instead of active planning of orders and trips.

Table 3.7: Available options for the building block task and skills.

	Variable	Options
Tasks	Driving	➢ Driver ➢ Remote operator ➢ Remote monitor
	Unloading	➢ Driver ➢ Yard personnel ➢ Automated
	Decoupling	➢ Driver ➢ Yard personnel ➢ Automated
	Planning	➢ Automated ➢ Human planner

3.3.3 Organization

Organizational roles and value chain configurations
The introduction of autonomous vehicles has a potential to shift and/ or introduce new organizational roles and responsibilities.

Based on earlier research, we identify several organizational roles and responsibilities [10]:

- **Vehicle Ownership** – the organization that owns the autonomous vehicle.
- **Digital Infrastructure** – the organization responsible for installation and maintenance of the digital infrastructure and connectivity required for communication with and between autonomous vehicles.
- **Transport Planning** – the organization that is responsible for making transport planning, coupling transport demand (of shippers, customers) with transport supply (autonomous vehicles to execute the transport.
- **Autonomous Vehicle-Logistics Interface** – this new role emerges with the introduction of autonomous transport. The autonomous vehicle needs logistics information to know what tasks to execute. And logistics systems need to be linked to the control tower that monitors the autonomous vehicle. An organization needs to be in charge of ensuring the link between the autonomous vehicle and logistics systems, which we describe as the autonomous vehicle-logistics interface.
- **Operating Control Tower** – this new role emerges. The control tower sends detailed assignments to the vehicle (e.g. regarding origin, destination, route, road segments) and monitors the execution of these. An organization needs to be responsible for operating the control tower daily. Without monitoring or remote operation at the control tower, the autonomous vehicle cannot drive.
- **Transport Execution** – The organization that is responsible for executing transport: driving the vehicle and handling the cargo.

Generally, we can group the main players in the transport ecosystem into the broad categories of OEMs – vehicle suppliers, transport companies – organizations planning and executing transport, and shippers – organizations with transport demand, all having different backgrounds and core capabilities. With the introduction of Connected Automated Transport, also new actors enter the ecosystem such as network providers with core capabilities related to connectivity (e.g. 5G networks) and new actors emerging such as automation providers – organizations that develop hardware and software for autonomous driving. This creates new interrelations between the different stakeholders, and many different configurations can be envisioned.

As the ecosystem of actors is still in development [10], we provide a starting point for discussion in our approach, by limiting ourselves to five different value chain configurations:

- **Traditional model** with roles comparable to current transport operations.
- **Transport companies in the lead (+)**, with high increased responsibilities for transport companies.
- **Transport companies in the lead** with moderately increased responsibilities for transport companies.
- **Automation providers in the lead**, with the new actors having a central role in not only linking logistics systems to the autonomous vehicle but also planning and controlling transport movements.
- **OEMs in the lead**, where original equipment manufacturers also have responsibilities in linking the vehicle they provide to logistics systems and operating the control tower of the vehicle.

By no means, these are the only configurations possible. Rather we consider these as starting point for discussion with the stakeholders involved in the logistics use cases.

Depending on organization strategy and preferences, the desired role and perceived advantages and disadvantages of a configuration can vary within the same group of stakeholders. Different transport companies can value their own position differently, although they belong to the same stakeholder group.

Table 3.8: For the building block ‘Organizational roles and value chain configurations’ there is one choice to make, the value chain configuration. This table explains what the different configurations mean and who is responsible for which topic.

Value chain configuration	Vehicle ownership	Digital infrastructure	Planning transport	Autonomous Vehicle – Logistics Interface	Operating control tower	Execution of transport
Traditional value chain	Transport company	Network provider	Transport company	Automation provider	Automation provider	Transport company
Transport company in the lead+	Transport company	Network provider	Transport company	Transport company	Transport company	Transport company
Transport company in the lead	Transport company	Network provider	Transport company	Automation provider	Transport company	Transport company
Automation providers in the lead	Transport company	Network provider	Automation provider	Automation provider	Automation provider	Transport company
OEMs in the lead	OEM	Network provider	Transport company	OEM	OEM	Transport company

3.3.4 Laws and Regulations

Autonomous vehicles operating in yard environments must comply with regulatory frameworks. Yard specific vehicles such as trailer movers, swap body movers and terminal tractors must comply with the EU Machine Directive. Overall, with respect to most regulations, OEMs are in the lead for meeting compliance requirements.

In current commercial projects (APM terminals, QTerminals Kramer Rotterdam), we observe that next to OEMs complying with the Machine Directive, a lot of attention is paid by both logistics partners and OEMs to execute safety and risk assessments. In the end, the yard operator is responsible for safety on its yard. So, for every risk that cannot be addressed by mitigating measures in technology or yard design, the yard operator must sign off all remaining risks.

When transferring beyond the yard, to public road applications such as industrial zones or long-haul corridors, other regulations apply. For this we refer to [10].

Table 3.9 Regulations for CAT at yards.

Legislation/ regulation	Description	Remarks
EU Machine directive - EU 2023/1230	Ensures that vehicles meet essential health and safety requirements, supported by harmonized standards such as ISO 3691-4 and ISO 13849.	There is a distinction between CE marking (self-assessment) and CE certification. The latter requires CE examination by a Notified Body (e.g. Tüv).
ISO 3691-4	This governs driverless industrial trucks such as AGVs, specifying requirements for obstacle detection, protective zones, and emergency stop functions.	
ISO 13849	Defines performance levels for safety-related control systems, ensuring that braking, steering, and other critical functions meet reliability targets.	Complements ISO 3691-4
ISO 21448 (SOTIF)	Addresses safety of the intended functionality, particularly for perception and decision-making systems that may not fail but still behave undesirably.	
UL 4600	Offers a comprehensive framework for documenting the safety case of autonomous systems, including fallback strategies and human-machine interaction.	
ISO/SAE 21434	Ensures cybersecurity compliance, protecting the vehicle from remote attacks and unauthorized access.	
EU Occupational Safety Directive - 89/391/EEC	Obligates employers to assess risks and implement preventive measures to protect workers interacting with autonomous systems	
ISO 12100	Provides the foundational methodology for risk assessment, guiding engineers in identifying hazards and implementing mitigation strategies.	

3.4 Interrelations

In the previous section, we introduced the individual building blocks and their possible options. This section explains how these building blocks relate to one another and how these relations ensure that all building blocks are coherently aligned into a consistent and realistic CAT design. The relationships between building blocks serve two main purposes: deriving new results and avoiding contradicting outcomes (and hence ensuring a coherent CAT design where all building blocks are aligned).

Deriving new results
Certain inputs naturally imply additional information. By using these interrelations, the system can derive results that were not explicitly provided.

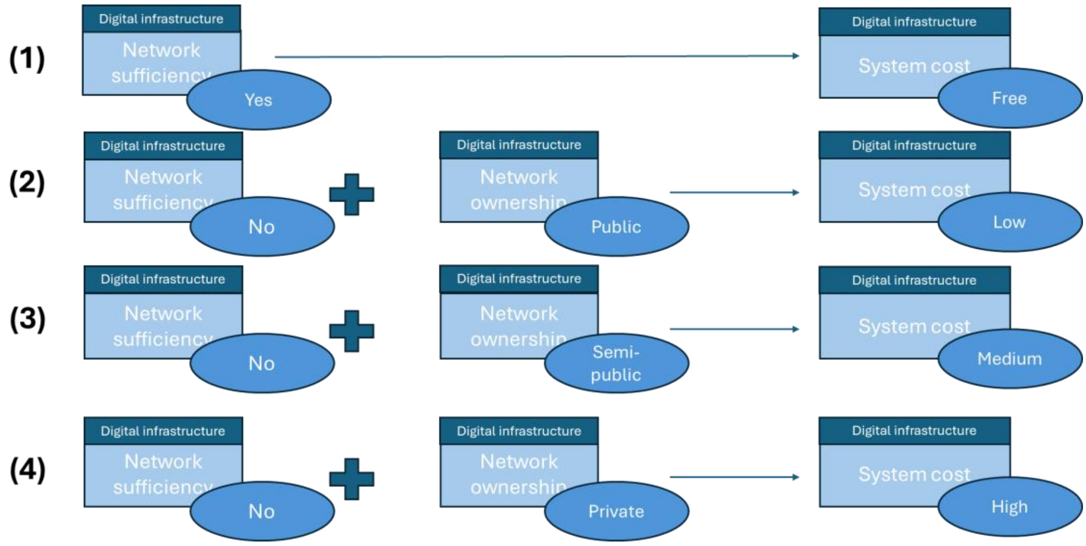


Figure 3.3: Four examples of the relationships that produces a new result, is the determination of system cost, which depends on the combination of connectivity sufficiency and network ownership.

Avoiding contradictions

The relations also ensure that impossible or inconsistent combinations are identified and rejected.

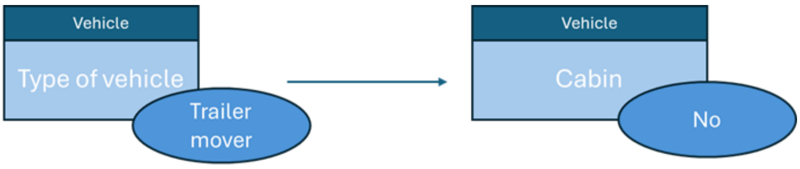


Figure 3.4: An example of a relationship where contradictions are avoided. Trailer movers do not have cabins. Selecting both ‘Trailer mover’ as the vehicle type and the ‘cabin’ option leads to an error.

In some cases, interrelations not only affect which options are valid but can also determine whether certain entities are required. These dependencies can operate in both directions, either from a chosen option to a required feature or from a required feature back to an implied option. For instance, if remote operation is required, TypeDB identifies this during an iteration. Consequently, the user must select in a next iteration a drive type other than “Manned”.

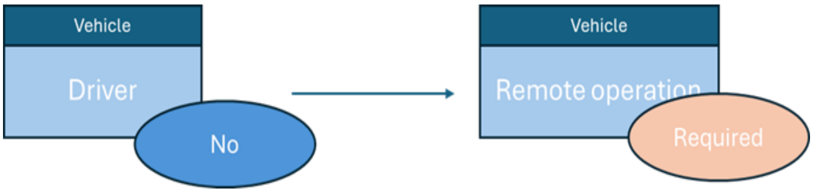


Figure 3.5: An example of a rule that enforces dependencies. In cases where no driver is present, remote operation must be selected.

Figure 3.6 illustrates how a choice in the Integration logistics work processes building block, specifically the selection of level of integration 3, affects multiple other building blocks.

Level 3 represents predominantly autonomous operation, with remote control only in specific situations, and enables continuous (24/7) operation. This choice impacts, on one hand, the vehicle-to-operator ratio within the Coordination & Control building block, and on the other hand, several elements of both Digital and Physical Infrastructure. Because level 3 removes the driver from the vehicle, additional capabilities are needed to support remote operation.

Finally, note that not all entities, or even all building blocks, are directly connected.
The complete list of interrelations is provided in Appendix A.

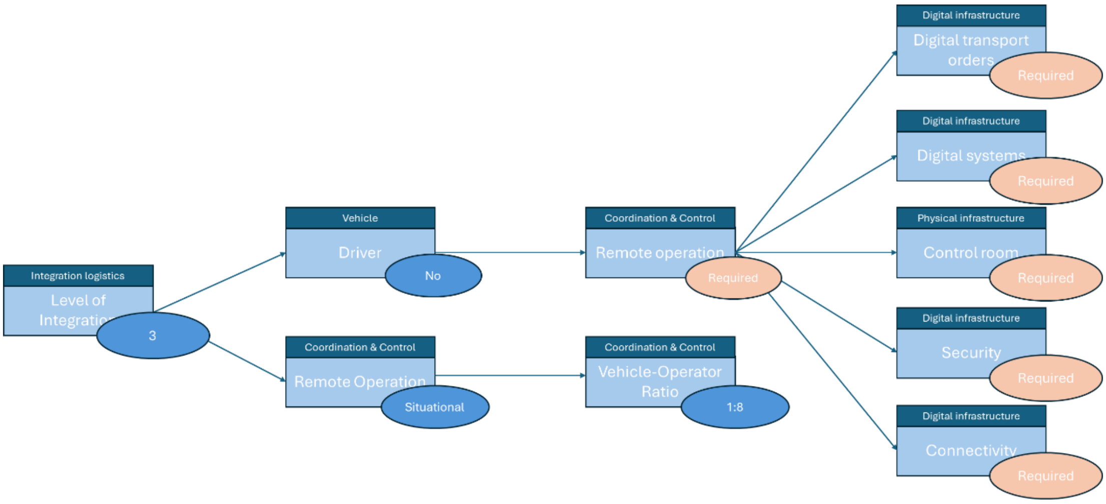


Figure 3.6: Impact of selecting Level of Integration 3 in the Integration Logistics work process on related building blocks. Level 3 enables mostly autonomous operation with limited remote control and affects the Vehicle-Operator Ratio, as well as digital and physical infrastructure requirements

4 CAT impact assessment

The previous chapter introduced the CAT integration building blocks and described how these building blocks are integrated in the requirements database for our method. The outputs of this database, described in section 3.2, form the foundation of the ex-ante impact assessment. This assessment aims to estimate the expected impact of implementing a CAT system, considering not only financial indicators such as costs, but also operational, organisational and environmental aspects, utilisation levels, emissions, safety, flexibility and implementation effort.

The purpose of the tool is not to produce detailed or deterministic predictions, the level of uncertainty is too high for that. Instead, it offers insight into potential challenges, major impact drivers, and the relative influence of different operational choices, such as fleet size or changes in operational hours. It is also designed to explore scenarios, such as scaling from one autonomous vehicle to a full fleet, identifying when a TCO-based business case becomes favourable, or assessing the impact of moving to 24/7 operations. It can even compare automation across multiple routes, including the effects of sharing digital infrastructure or remote operators. In this way, the ex-ante impact assessment supports strategic decision-making by illustrating how different configurations shape future operational performance.

4.1 Impact assessment framework

The impact assessment is based on two main types of input. First, the results from the CAT requirement database provide the CAT design characteristics - that are necessary for the calculation of the KPIs in the impact assessment - in the form of a constraints table. These include, for example, the vehicle-operator ratio used to determine the number of remote operators, the maturity of the digital infrastructure and whether additional systems are required, or the specifications that determine the control room size.

Second, the tool requires operational data from the use case itself. These inputs translate the CAT design into actual impacts and include information such as the number of trips per day, operational hours, distances, handling times, and labour costs for drivers and remote operators. These are filled in a dashboard and used in the Impact Assessment.

Furthermore, the assessment relies on a set of general (non-use case specific) assumptions (see Appendix B). These assumptions are applied across all use cases and define financial and technical parameters such as purchase prices, maintenance costs, energy consumption of vehicles, rest-time factors and effectiveness factors for drivers and operators. These are model parameters rather than user-defined inputs, though users can modify these.

Together, these elements define the modelling of future operations and enable comparison between autonomous and baseline scenarios. The overall workflow structure is illustrated in Figure 4.1.

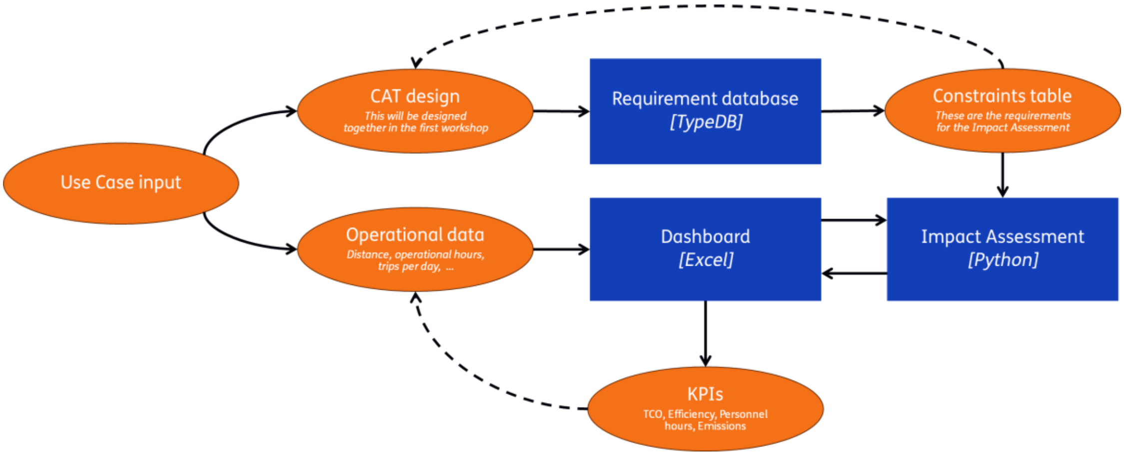


Figure 4.1: Structure of the tool used for the logistics centred design approach, showing the flow from use case inputs through the requirement database and impact assessment to the dashboard, where the KPIs are displayed. The feedback loops indicate the iterative nature of this process.

The tool evaluates both quantitative KPIs and qualitative results. Quantitative KPIs include costs, personnel hours, emissions and efficiency. Qualitative results, although not directly calculated using formulas, remain equally important. These include safety, flexibility and implementation effort. Quantitative KPIs are displayed via a dashboard, while qualitative results are discussed jointly with the use case participants.

4.2 Ex-ante impact assessment tool

This section explains how the impact-assessment tool uses the information from the requirements database, together with a set of assumptions and operational data, to calculate the key performance indicators (KPIs) for both the baseline and autonomous scenarios. By combining these different types of inputs, the tool can determine the required fleet size, personnel hours, emissions, total cost of ownership (TCO), and overall efficiency. The following subsections describe the inputs used and how they feed into the subsequent calculations.

4.2.1 Inputs

The input for the impact assessment consists of three elements: the results from the requirements database, the operational data from the use case a set of assumptions.

Results of the CAT requirements database
The table with the requirements results feeds directly into the tool and forms the basis of several calculations. From these results, we determine the expected purchase price of the vehicle based on the selected truck type and autonomy level, whether a control room is required and what size it should be, and which parts of the digital infrastructure are already sufficiently developed. If certain digital components are still missing, corresponding costs are added based on the maturity of the current infrastructure. The database also provides the vehicle-operator ratio, depending on the remote operation level, and any required adjustments to the operating speed (for example, when operating under level 1 of the logistics orchestration levels of automation).

Operational data
To model both the baseline (AS-IS) and autonomous designs (TO-BE), the tool requires several operational inputs from the use case. These include the number of trips per day, distance per trip, driving speed, operational days per year, and operational hours per day (including the share taking place during the night). The labour costs of drivers and remote operators are also needed. In addition, handling times for loading and unloading must be provided, and in the autonomous scenario the tool needs to know which part of the handling process can be automated and which still requires manual work. Optionally, the number of available (autonomous) vehicles can be given as input, in the case that the users wants to automate only a part of the fleet.

Assumptions
The assumptions applied in this analysis, which can be adjusted by the user to explore different scenarios, cover both financial and operational aspects, with a full overview and sources listed in Appendix B. For vehicle purchase price, the database outputs are combined with [8] assumptions to calculate the expected costs. Maintenance costs are assumed to be equal for autonomous and manned vehicles but depend on the powertrain and vehicle type (diesel or electric). For energy usage, we assume no structural difference between manned and autonomous vehicles. There is currently no reliable evidence to justify a distinction: autonomous vehicles might be more efficient due to, e.g., the lack of cabin heating and more consistent driving behaviour, but they also require additional power for cooling and onboard autonomous systems. Given these opposing effects and the insufficient insight in the relative impact, we treat the energy usage as equal.

The operational assumptions consist of a rest-time factor and an effectiveness factor. The rest-time factor is set at 0.125, meaning that a driver spends one-eighth of the operational hours on breaks. The effectiveness factor is 0.88, reflecting that drivers and remote operators are not productive during their entire available time and may spend around 12% of their shift on supporting or unavoidable non-driving or non-operator tasks. These operational factors influence how many trips a vehicle can perform within a day and thus affect the fleet size calculation. The values mentioned above are 'default' values, in consultation with the use case, these can be adjusted.

4.2.2 Quantitative analysis

After all inputs have been provided, the tool calculates the KPIs for both the baseline (manned) and autonomous CAT designs.
The first step is to determine how many trips a single vehicle can complete in a day. This depends on the distance, speed, operational hours, handling time, and the operational assumptions described in section 4.2.1. Based on this outcome, the required fleet size is calculated. When a fixed number of autonomous vehicles is specified in the input and this number is insufficient to complete the workload, the tool supplements the fleet with manned vehicles.

Once the fleet size is known, the total personnel hours can be calculated for both drivers and remote operators. Emissions follow from the total distance driven and the vehicle's powertrain (diesel or electric).

Costs are assessed using a Total Cost of Ownership (TCO) calculation inspired by the Panteia method for trucks [11]. Instead of considering vehicle purchase price solely, the TCO includes vehicle depreciation, variable costs such as energy and maintenance (which depend on kilometres driven), digital infrastructure costs (both per vehicle and for system-wide

components), and labour costs. It gives an estimation of the TCO for the whole operation per year. The TCO is also expressed per vehicle hour, which allows for business-case comparison between CAT designs and scenarios.
Labour costs are a key component of total operational costs and can be divided into effective and ineffective hours. Effective hours are the periods during which personnel are actively engaged in productive work, such as driving, monitoring, or performing necessary operational tasks. Ineffective hours, on the other hand, occur when personnel are not directly contributing to productive output. These can arise when drivers take breaks, wait during loading and unloading, or encounter other idling time in their workflow.
For remote operators, ineffective hours can be utilized more flexibly. For example, if vehicles are being loaded or unloaded, remote operators can perform other tasks (e.g. planning or administrative work) during this downtime, which reduces the cost impact of these ineffective hours. This distinction is important because it highlights potential efficiency gains that are unique to remote operations compared to traditional driving roles.
The last KPI the tool assesses is Efficiency, expressed as vehicle utilisation per vehicle. This is calculated by dividing the total working hours by the total available hours. It is useful to also look at utilisation over effective hours. When this is close to 100%, vehicles are fully used and cannot take on more trips. If it is lower, some vehicles are idle during operational hours, indicating potential to increase the number of trips with the same fleet.

4.3 Qualitative indicators

While KPIs such as costs, personnel hours, emissions, and efficiency provide measurable insights, qualitative indicators are also important for evaluating the broader impacts of implementing Connected Autonomous Transport systems. These indicators capture organisational, operational, and safety considerations that cannot be measured numerically, offering guidance for decision-making and highlighting potential indirect effects.
Regarding safety, we developed a framework to assess the complexity of the environment of the autonomous vehicle. Regarding flexibility and effort of implementation we took a slightly different approach. For these indicators, we point towards important considerations to consider and do not have a (normative) framework. As we also discuss in the future research section, we recommend to further develop this. Nonetheless, by providing stakeholders guidance in important considerations, we already can identify relevant boundary conditions.

4.3.1 Safety

We have opted for a high-level analysis that can reflect the challenges involved in implementation and make suggestions for mitigating measures. The method distinguishes the most important safety aspects that play a role for an autonomous vehicle in a chosen operational design domain (ODD).

We divide the functionality of the vehicle into three categories: sense, plan and act.

- **Sense** includes the aspects that influence the sensors used to perceive the environment.
- **Plan** includes everything that is important for understanding the situation and determining what actions the vehicle should take.
- **Act** describes the challenges that an autonomous vehicle may face in driving safely and carrying out the planned actions.

We defined three levels of complexity for each safety aspect: low, medium and high. In the analysis, we examine which level applies in the CAT design. In addition to qualifying the complexity, the framework also contains suggestions for mitigating measures.

These are measures that can be taken to increase safety and reduce the complexity of a particular safety aspect. On the one hand, these may be measures relating to the chosen vehicle, for example by choosing a vehicle with different technical specifications that can better cope with a particular complex situation. On the other hand, it is also possible to adapt the environment, for example by making infrastructural changes or choosing a different route. In Appendix C we provide the entire safety assessment table. In Table 4.1, we show a fragment of the full framework for illustrative purposes.’

Table 4.1: Safety assessment framework – fragment for illustrative purposes.

	Low level of complexity	Medium level of complexity	High level of complexity	Mitigating measures - vehicle	Mitigating measures - surroundings
Sense (perception – lighting conditions)	Fair weather	Bright low sun / Dark, with streetlamps	Dark, no streetlamps	Install additional lights on the vehicle, adjust sensor technology for object detection under complex lightning conditions;	Install additional lights on the terrain.
Plan (traffic conditions – crossings)	Easy (e.g., right turn / dedicated traffic lights / right of way)	Moderate (e.g., straight / general traffic lights)	Hard (e.g., left turn / no traffic lights / no right of way)	More advanced perception system, and behaviour prediction and planning algorithms, V2I communication.	Alternative trajectory, infrastructural changes (e.g., traffic lights, barriers), traffic rules (e.g., right of way for ADS); sensors on infrastructure with V2I communication
Act (driving – road surface quality)	Good (e.g., smooth asphalt)	Medium (e.g., irregular / multiple surface types / some potholes)	Bad quality (e.g., many potholes)	More advanced position control (e.g. more forgiving w.r.t. position error); ESP; ESC	Regular road maintenance

4.3.2 Flexibility

Flexibility describes how well a CAT system can adapt to changes in operations, such as adjusting schedules, routes, or workload distribution. There is not one generic way yet to assess flexibility.

When analysing a use case, we suggest discussing flexibility with the stakeholders of the use case under consideration:

- ☐ **CAT can reduce reliance on unpredictable personnel** and **increase operational flexibility**. Automating vehicle movements can make operations more stable and predictable by reducing dependence on human workers, who may be unexpectedly unavailable due to sickness or other disruptions. In addition, CAT enables remote operators to supervise or support multiple vehicles or tasks simultaneously, offering new opportunities to organize workflows more flexibly and efficiently.

- **Technology choices** for CAT may introduce new constraints and **reduce operational flexibility**.
    - For example, selecting a vehicle without a cabin means the vehicle can only operate autonomously. In exceptional or unforeseen situations, no human driver can take over physically, which might be limiting operations.
    - Or, for example physical infrastructure adaptations, such as dedicated lanes or redesigned intersections, might be required for optimal implementation of CAT. These adaptations can improve safety and operational efficiency and traffic flow but involve upfront investments and additional costs for reversing these adaptations.

  CAT design choices like this can be fully acceptable, but it requires careful consideration and evaluation with the other impact indicators.

The actual impact of the CAT design on flexibility depends heavily on the use case. In controlled environments or dedicated lanes, operations can be highly dynamic, while in mixed traffic or highly regulated areas, flexibility may be more limited. Therefore, in the Logistics Centred Design Approach sessions (see CH5), we have discussed possible advantages and drawbacks in terms of flexibility with the CAT4Yards logistics partners.

4.3.3 Implementation effort

By implementation effort we refer to the qualitative measure of how much work is required to transition from a manned to an unmanned operation whereby Connected Automated Transport is integrated in logistics. At this stage, there is no framework yet to assess this indicator. We therefore recommend discussing implementation effort directly with stakeholders when analysing a specific use case.

The following steps can guide this discussion:

- Analyse the current manned operation using the CAT building blocks and compare it with the required changes for each proposed CAT design. Together with stakeholders, explore how many changes are needed and how substantial those changes are. Discuss the timeline and pace of implementation that would be feasible or required: step-by-step and incrementally, or more rapidly.
- Discuss the organization’s history and culture and draw on past experiences with change initiatives to explore how these could influence the effort needed to implement CAT. Depending on those experiences, organizations may find it easier or more challenging to implement changes that are required for Connected Automated Transport.

5 Logistics centred design approach – step by step guide

As described in [7], the rationale behind the Logistics Centred Design Approach Connected Automated Transport is that the focus lies on the logistics operation rather than the technology itself. The goal is not to implement CAT at all costs, but to adopt it only when it delivers favourable outcomes – enhancing efficiency, safety, predictability, and sustainability for future-proof logistics.

We distinguish three main phases: problem **definition**, solution **implementation** and **validation and improvement** (see
Figure 5.1). The different steps of these three phases are linked to iteratively improve and develop a CAT solution for logistics. In short, the phases consist of the following:

1. **Definition phase**: Defining the current (AS-IS) situation of the logistics operation and setting boundary conditions for the possible future (TO-BE) situation when CAT is implemented.
2. **Implementation phase**: Virtually designing and implementing potential CAT designs and impact assessment. Through designing possible futures or 'what-if situations' one constructs a CAT design for the intended situation: the TO-BE situation. In the impact assessment we compare the AS-IS and the TO-BE situation to gain insights to the changes in logistics KPIs that can be linked to the CAT design.
3. **Validation and improvement phase**: Selecting and refining the preferred CAT design and identification of the next steps towards testing, implementation and scaling of the CAT solution in a specific logistics use case.

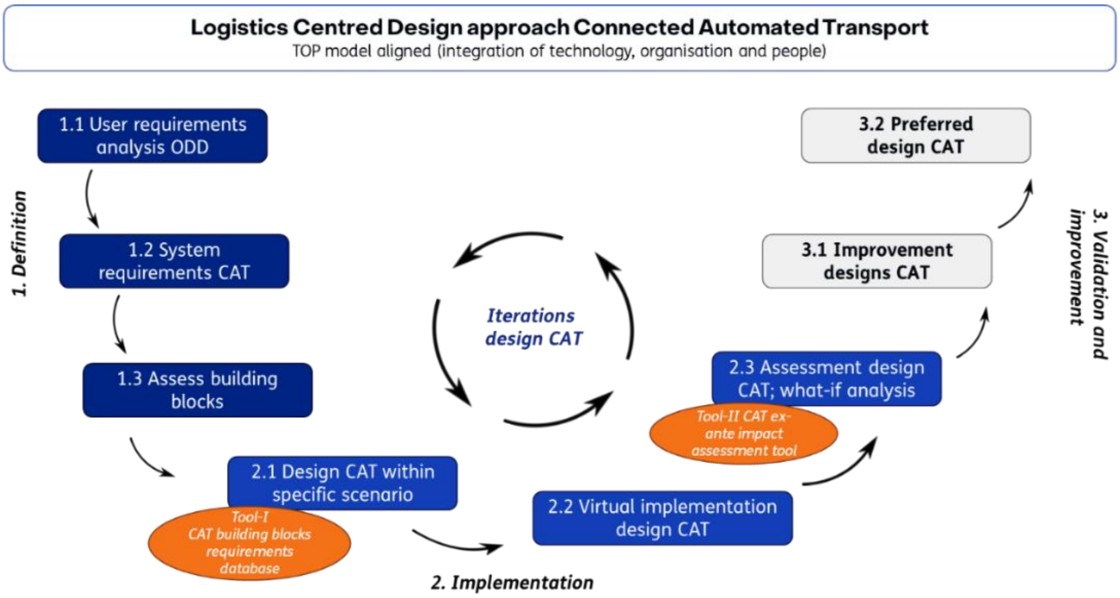


Figure 5.1: Logistics Centred Design Approach Connected Automated Transport.

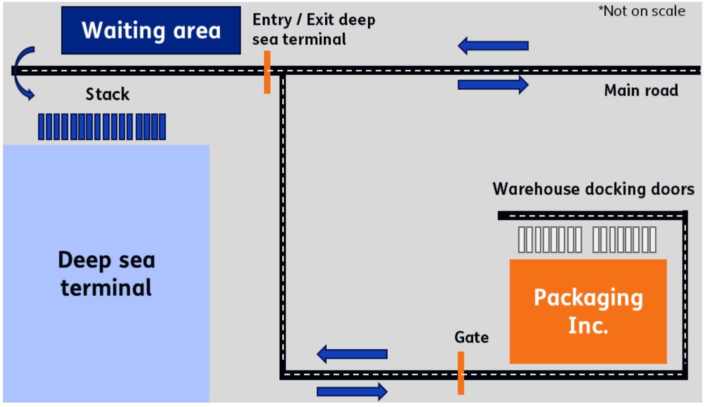
We present the steps of the Logistics Centred Design Approach in more detail in the sections below, using an illustrative fictive use case that shows the application of the methodology. To execute the Logistics Centred Design Approach for a logistics use case, we suggest following a workshop-format as presented in paragraph 5.4 and Appendix D.

5.1 Definition phase

The goal of the definition phase is to get a clear understanding of the current (AS-IS) situation of the logistics operation and possible boundary conditions for the CAT design, through the following three main activities:

a) **User requirements analysis ODD** - Specifying the logistics operation and the Operational Design Domain (ODD). Then, analysing the current logistics operation (among others, through a step-by-step process analysis and outlining the transport route under consideration on a satellite map) and describing the logistics user needs and expectations regarding CAT.
b) **System requirements CCAM** – Using input from [1.1], setting intended goals for the CAT design. Specifying whether there are any system requirements or boundary conditions that should be considered.
c) **Building blocks assessment** – Translating the user expectations and requirements, system requirements and boundary conditions to the conceptual framework CAT building blocks (see section 3.3). By this, one gets a clear overview of what factors to consider when developing the CAT designs in the next step.

BOX 1 – CAT transport at a container yard: Definition phase
In this illustrative use case, we consider TransportCo who transports containers between a Deep-Sea terminal and Packaging Inc. The main reason for exploring autonomous transport is personnel shortages in combination with expected transport volume growth. TransportCo wants to anticipate for these future changes. Below a schematic picture of the yard lay-out is displayed, as well as the input values for the AS-IS manned operation and the TO-BE autonomous operation.



	AS-IS	TO-BE
Trips per day	60	60
Distance	4	4
Velocity	20	15
Operational days	260	260
Operational hours (night)	12(4)	12(4)
Hourly wage operator	-	50
Hourly wage driver	45	-
Handling time	9	5
Waiting time	8	10

5.2 Implementation phase

The implementation phase concerns designing coherent CAT designs and comparing these with the AS-IS manned operation.

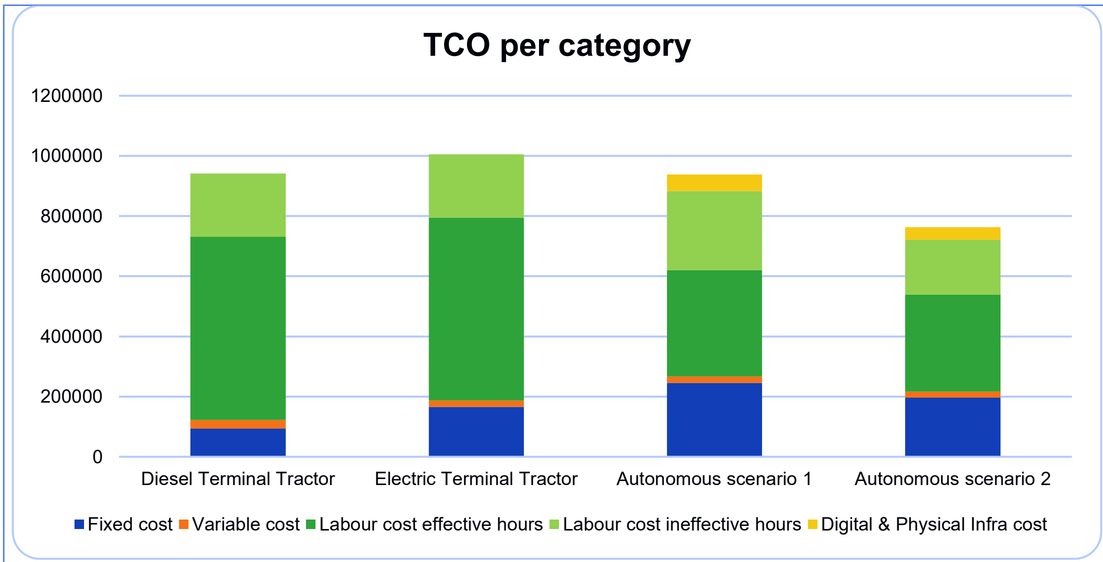
We distinguish the following main steps:

- **1.1 Design CAT within a specific scenario -** Based on step [1.3], create a coherent CAT design where all CAT building blocks align making use of the CAT requirements database If some boundary conditions are unclear, check with the logistics user or make assumptions. This is an iterative process with steps [1.2] and [1.3].
- **1.2 Virtual implementation of CAT design -** Using the requirements and design from [2.1], virtually implement the CAT design, compare it to the current AS-IS situation, and assess impacts with the CAT ex-ante impact assessment tool (see 3.2.2). Not all effects can be quantified, so describe qualitative impacts as well.
- **1.3 CAT design assessment & what-if analysis -** Finally, compare outcomes with initial CAT goals [1.2]. Multiple CAT designs can be developed for comparison. Perform what-if or sensitivity analyses to address uncertainties (e.g., future autonomous vehicle costs).

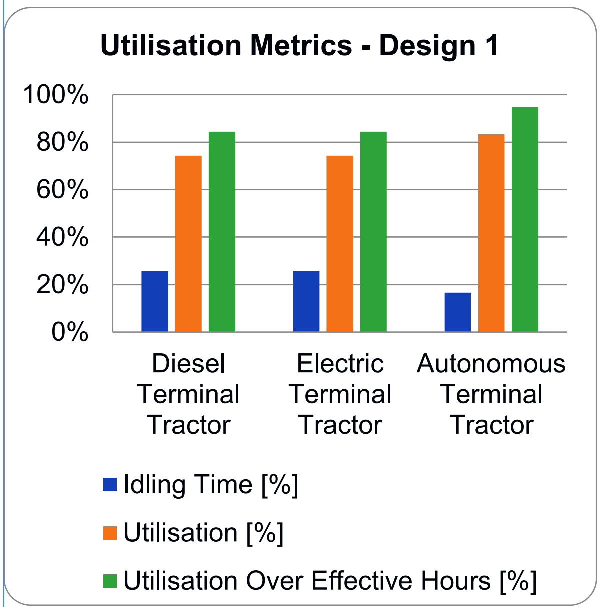
BOX 2 – CAT transport at a container yard: Implementation phase

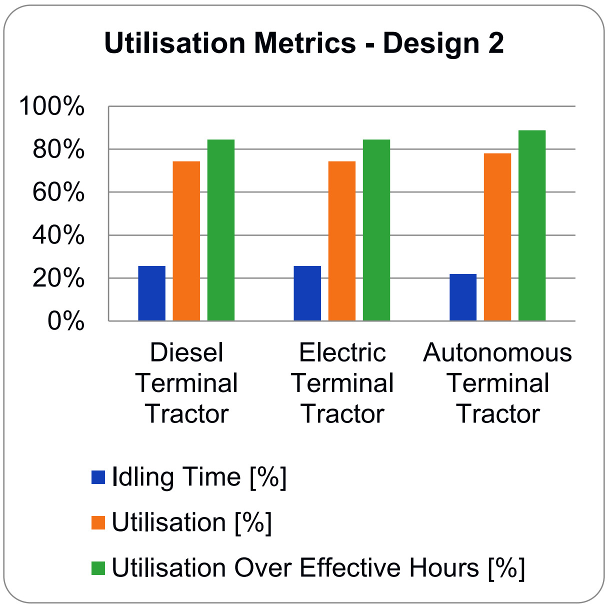
For TransportCo's transport between Packaging Inc. and Deep-Sea terminal, we consider two CAT designs. In Design 1, autonomous transport is applied to replace the current operation. Design 2 investigates fully autonomous transport where the operational hours are increased from 12 hours a day to 16 hours a day. For both these designs, the ex-ante impact assessment is applied to estimate costs, operational efficiency, personnel hours and emissions.

The following figure represents the TCO for the baseline and the two autonomous scenarios. Design 1 shows a cost advantage compared to the baseline, although the cost reduction is limited. In Design 2, the TCO is substantially lower. This indicates that increasing daily operational hours improve here the TCO performance. The main reason for this is that extending operational hours eliminates the need for a fifth vehicle. This reduction not only lowers vehicle costs, but also decreases labour costs, as four vehicles require only one remote operator instead of two.



Looking at the logistics efficiency, if we compare the two designs, we see that in both designs the utilisation of the autonomous vehicle is higher than the baseline vehicles. However, Design 2 (right) is slightly lower compared to Design 1 (left). This means that in Design 2, the autonomous vehicles are slightly more ineffective, but there is more potential growth of transport compared to Design 1.





Furthermore, other KPIs are personnel hours and emissions. We see that the personnel hours are reduced from 15600 hours to 6240 in Design 1 and to 4160 hours in Design 2, since only one remote operator is needed.

The emissions are reduced from 28000 kg CO_2 and 239 kg NO_x to zero, although this is fully because of switching to electric vehicles.

The main complexity with regards to safety is the mixed-traffic and chaotic situation at the port. A lot of different traffic and trucks drive in the port-area as well. The autonomous vehicle must cope with this in a safe and efficient manner. It is important that the digital map of the yard is always up to date. This way the vehicle will not be hindered by randomly placed containers or other structures.

5.3 Validation and improvement phase

In the validation and improvement phase the aim is to select and refine the preferred CAT design and define next steps for testing, implementation, and scaling within a specific logistics use case, consisting of two main activities:

3.1 **Improvement CAT designs -** Using results from the ex-ante impact assessment [2.2] and what-if analysis [2.3], hold discussions with the logistics organization to explore possible improvements and adjustments to the most promising CAT design. Summarize differences between the CAT design and current operations.
3.2 **Selecting preferred CAT design -** Based on these discussions, choose the most suitable CAT design and agree on next steps. These may include additional analyses (e.g., simulation studies), developing a test plan, or engaging potential technology suppliers.

BOX 3 – CAT transport at a container yard: Validation and improvement phase
The results in BOX 2 show that the autonomous design with extended operation (Design 2) has a lower Total Cost of Ownership compared to 1-on-1 replacement of the current operation (Design 1). Furthermore, there is a higher potential of increasing the total volume of transport without adding additional vehicles in this scenario. However, it is important to keep in mind that 1) the receiving warehouse must be able to operate 16 hours a day or receive vehicles for that amount of time. Depending on the tasks that currently the driver is doing, there are additional efforts required to replace the driver. Either by automating the task or have other personnel take over the task. So as one of the next steps, additional analyses on the receiving warehouse is recommended to verify the feasibility of extending operational hours.

5.4 Workshops for executing the ogistics centred design approach

When analysing a logistics use case of whether and how to integrate Connected Automated Transport in logistics processes at a yard, we suggest using a workshop structure to execute the Logistics Centred Design Approach. In at least 3 workshops sessions with the ‘owner’ of the logistics use case the required information to develop and analyse several CAT designs, what-if analyses, and next steps are discussed (
Figure 5.2). The workshops follow roughly the three different phases of the Logistics Centred Design approach: Definition, Implementation and Validation and Improvement.

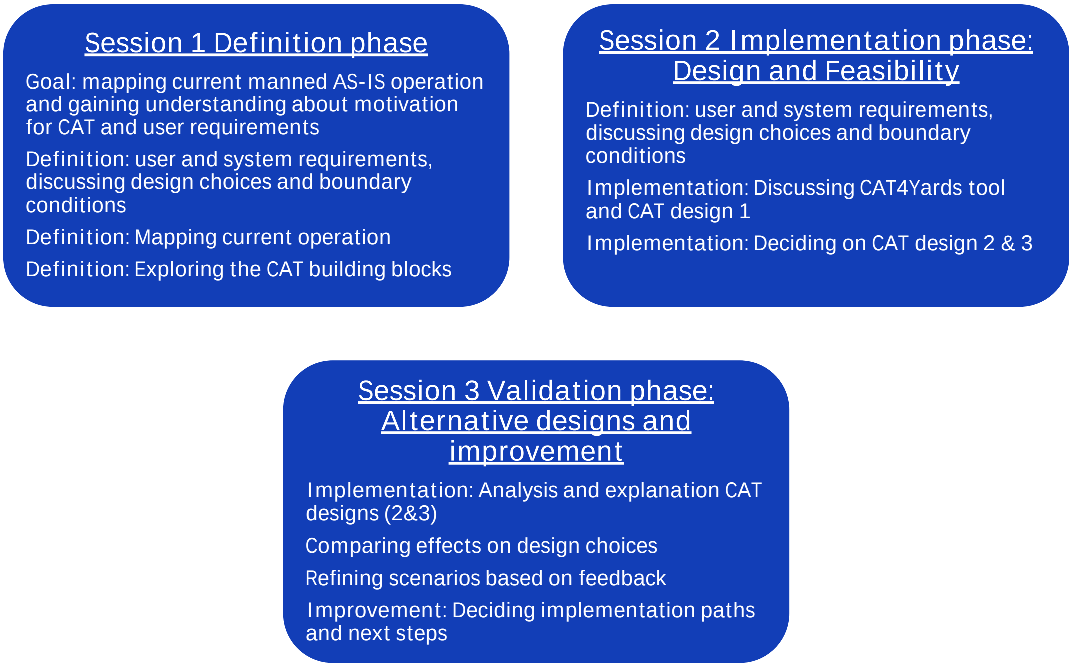


Figure 5.2: Workshop sessions overview.

We advise take enough time to go through all steps of the Logistics Centred Design Approach in one day, as this can be quite overwhelming for the logistics organization involved. Time is needed for the involved participants of the workshop to capture the breadth and depth of all CAT building blocks and the possible CAT designs that these could hold. In Appendix D we provide a step-by-step workshop template that – if desired – can be tailored to the involved stakeholders' needs. It makes quite a difference if the organisation already has prior knowledge on Connected Automated Transport. We suggest tailoring the sessions to the level of prior knowledge and – if applicable – also tailor the persons present in the sessions. For example, in the first session also general managers can be present whereas for the second session one might also need specialists. The workshop format and approach is set up as such that it can be applied to logistics yard use cases beyond the specific scope of the use cases that we used to develop this method.

With respect to the analyses in the implementation phase, these can be executed in the time between the workshops, or partially during the workshops. Within the supporting tooling of the Logistics Centred Design Approach, it is possible to conduct analyses during the workshop and present the outcomes of the quantitative ex-ante impact assessment in a dashboard. The dashboard is a useful supporting tool that enables what-if calculations during the workshops.

An alternative approach to follow the workshop format, one can choose to collect the required information and hold the discussions in multiple shorter 1-1,5-hour interview sessions. For doing so, the questions in Appendix D and the data collection templates in Appendix E can be applied.

6 Lessons learned from CAT4Yards use cases

We developed and validated the Logistics Centred Design Approach in three different use cases (Figure 2.3). In this chapter we summarize the overall lessons and observations of the methodology and integrating CAT in logistics yard operations, starting with the four main lessons:

1. **Coordination and control is a key building block for integrating CAT at yards**
   Of all building blocks, we identify coordination and control as a critical element in the overall CAT system design. This building block must be closely aligned with vehicle specifications, digital infrastructure - particularly connectivity requirements - and necessary adaptations to physical infrastructure, which in turn affect traffic flow and safety. It is also strongly linked to the tasks of personnel. We elaborate on the role of remote operators: in some situations, real-time remote control is required, placing high demands on real-time connectivity and system reliability, whereas in other cases remote assistance is sufficient, involving message exchange and operator approval rather than direct control. Finally, the operator-to-vehicle ratio emerges as a key design parameter, significantly influencing system design and overall total cost of ownership.
   - ➢ Logistics companies should explicitly discuss the above with vehicle manufacturers and automation providers in an early stage to assess their preferences against current and near-term technological capabilities and their value propositions.

2. **Process standardization, digitization and task redesign are prerequisites for integrating CAT into logistics operations**
   To enable effective digital communication between logistics systems and autonomous vehicles, existing logistics processes must first be standardised and digitised. In addition, careful attention is required for the non-driving tasks traditionally performed by drivers. These tasks can be addressed through a combination of measures, such as extending vehicle functionalities, adapting logistics processes – for example by reallocating tasks to other human operators, or deploying complementary technological solutions for (un)loading vehicles or (de)coupling trailers. The choices made have implications not only for system design, efficiency and viability of the business case, but also for the attractiveness and future role of remaining human tasks within logistics operations.
   - ➢ Logistics companies should start by standardising and digitising their main logistics processes and by mapping non-driving tasks. Then, they should explore how to organize these tasks differently while aligning technology, operations and workforce.

3. **Understanding cost drivers through sensitivity analysis strengthens strategic CAT decisions**
   Explicitly accounting for uncertainty in technological developments strengthens strategic decision-making for CAT. By applying sensitivity analyses in the ex-ante

impact assessment, the approach deliberately works with orders of magnitude and bandwidths instead of overly precise figures. This provides realistic and actionable direction for logistics companies at the current stage of CAT maturity. The analysis shows that vehicle costs are a dominant cost element in most CAT designs and therefore a critical driver in overall business case viability. Digital infrastructure costs are relatively smaller in comparison, but they can increase depending on connectivity requirements - particularly in cases that rely on real-time remote control or high system availability. Presenting costs in ranges helps companies understand which parameters matter most, anticipate how costs may evolve over time, and identify where design choices can considerably influence total cost of ownership.

- ➢ Logistics companies should pay close attention to the sensitivity analyses in the ex-ante impact assessment as these accommodate for uncertainties in CAT development over time. Focusing on orders of magnitude and key cost drivers helps prioritizing and trading off the KPI's of the various CAT designs.

4. **Exploring multiple CAT designs enables outlining transition path**

Assessing CAT designs that range from configurations close to current manned operations to more creative or partial implementation provides valuable insight into where and how organizations can take their first steps. The approach provides the opportunity of explicitly weighting impact indicators: while total cost of ownership is often central, factors such as personnel availability and safety can be equally important in evaluating CAT designs. The approach enables evaluation of different implementation paths. Starting small increases costs and effort per vehicle, while starting large improves this but may impose changes that are too demanding for current operations.

- ➢ Logistics companies should assess several CAT designs in parallel, including ones that are more 'out-of-the box'. Additionally, they should define which impact indicators matter most for their strategic objectives. Being explicit about the relative importance of performance indicators enables clearer prioritization of CAT designs, contributing to well-founded decisions for a transition path towards CAT implementation.

6.1 Value for logistics companies

The different use cases are described in detail in company-specific deliverables. For confidentiality reasons, we highlight the value of the Logistics Centred Design Approach Connected Automated Transport for the logistics companies in an anonymized way:

- **Clear direction** – The approach provides concrete guidance on where to start when exploring CAT, reducing uncertainty in early decision-making.
- **Validation of fundamentals** – It confirms key building blocks and relevant boundary conditions for implementation.
- **Evidence-based confidence** – The ex-ante impact assessment convinces companies that CAT is a viable innovation to make their logistics operations future-proof. Stakeholders can confidently find organizational support for narrowing down promising applications in their organization.
- **Process readiness** - The approach serves as a catalyst for systematically mapping, and where necessary, adapting yard and logistics processes in preparation for CAT.
- **Improved market dialogue** - The approach generates concrete inputs for informed discussions with vehicle manufacturers (and automation providers).

- **Strategic insight in transition path –** The approach provides clarity on feasible transition paths toward CAT. While the transition phase may not be directly commercially viable for some organizations when assessed purely on total cost of ownership (TCO), the final CAT design can be economically viable. Organizations with sufficient strategic vision and committed resources are therefore able to successfully bridge the transition period and realize intended benefits.

7 Conclusions and Outlook

In this report we presented the Logistics Centred Design Approach Connected Automated Transport. We outline the process steps and provide more in-depth background on the conceptual work and the supporting tooling: the CAT building blocks requirements database and the ex-ante impact assessment tool.

With this approach, we make important steps to bridge the gap between logistics companies and OEMs. Our approach guides logistics companies to make start with Connected Automated Transport. The approach serves as a conversation starter among the involved stakeholders - especially logistics companies – enabling them to make informed decisions in a structured way on the next steps towards CAT deployment at their yards.

The Logistics Centred Design Approach provides insights into the conditions required for successful CAT integration, the necessary efforts related to technology, logistics and organization, and the associated impacts based on both quantitative and qualitative indicators. Through ‘what-if’ analyses, logistics companies can safely explore different CAT designs and scenarios to identify the most beneficial and feasible path forward. This reduces uncertainties around CAT implementation and makes its concrete value clearly visible.

The methodology and tooling were developed and validated using three real-world use cases and deliberately designed to be applicable to other cases. This allows them to be used in similar logistics situations and to support other organizations in deciding how to move forward with Connected Automated Transport. Other logistics parties have already expressed interest in applying the approach in their own cases.

7.1 Outlook on CAT development

While our Logistics Centred Design Approach is an important step with respect to preparing the (Dutch) logistics sector for Connected Automated Transport, it does not end here. First, we make a few suggestions to further improve the Logistics Centred Design approach for yards. Second, we present the outlook on CAT development beyond preparational studies (like this one) at yards.

Logistics Centred Design Approach CAT at yards
First, some of the inputs for assessing impacts are uncertain (a.o. vehicle purchasing price, costs of digital infrastructure). We mitigated this by incorporating sensitivity and what-if analyses in our approach. Identifying and discussing these sensitivities is central in the workshop format with logistics stakeholders. Despite these measures we recommend updating input values, as new knowledge becomes available. The modular set up of our method and tooling enables this.

Furthermore, as knowledge progresses, we also expect that more fine-grained analyses can be made with respect to the more qualitative impact indicators such as safety, and effort to change and that it might be possible to make these more quantifiable as well.

Further advancing CAT for safe, efficient, sustainable transport
The Logistics Centred Design Approach is a starting point for logistics companies making informed decisions on the next steps on Connected Automated Transport. We envision two directions in which Connected Automated Transport should be enhanced: extension of application area and moving into real-world trials (see
Figure 7.1).

A logical next step is to gradually increase the complexity of ex-ante impact assessments by incorporating additional application areas beyond yards, including public roads with potential for Connected Automated Transport: Industrial Zones (short distances <5 km), Regional Transport, and Long-Haul Transport (extended national and international corridors). Figure 7.1 presents this progression on the horizontal axis from left to right. We envision knowledge exchange wherever it adds value and understanding (the circle arrows in Figure 7.1). The grey shaded area with the dotted line indicates that a follow-up project is in development that covers these application areas.

A second essential follow-up step is moving from ex-ante impact assessments to real-world trials, as shown on the vertical axis in
Figure 7.1. The grey shaded area with the dotted line indicates that follow-up projects are in development that cover these real-world trials. Ultimately, logistics companies gain the most from pilots that go beyond testing technological functionalities and focus on integrating autonomous vehicles or CAT concept into operations through learning-by-doing. Monitoring these real-world demos is important to record lessons learned.

Furthermore, in this phase, ex-post impact assessment becomes crucial to evaluate effects on logistics operations - such as costs, personnel, efficiency, sustainability, and safety - and to compare these with ex-ante predictions. This process deepens logistics companies' understanding of CAT and enables more accurate forecasts for future use cases.

Such insights also support efficient roll-out and scaling of CAT concepts whenever they prove beneficial and desirable, contributing to safer, more sustainable, and more efficient transport.

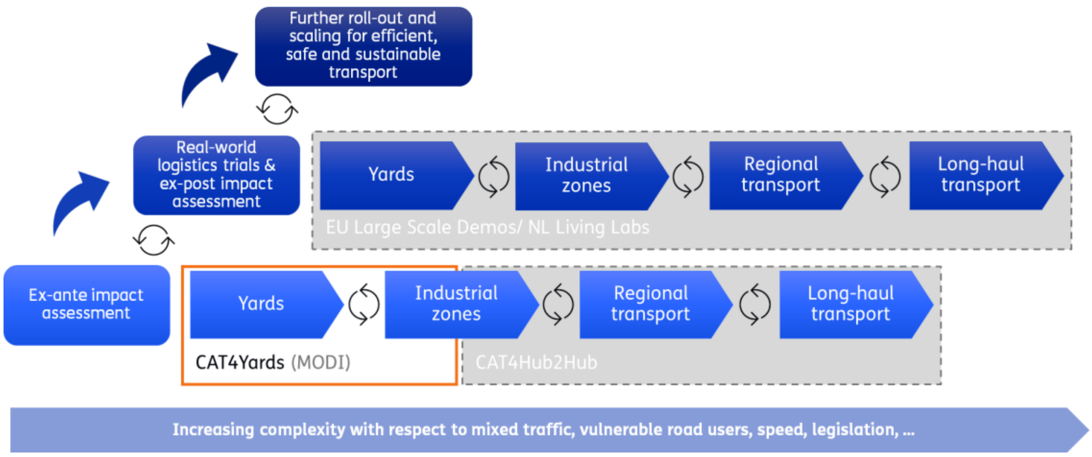


Figure 7.1: Outlook development Connected Automated transport in the Netherlands (projects in grey areas in development).

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Signature

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Appendix A

Complete list of interrelations between building blocks

Vehicle Table A.1: and coordination and control rules.

IF	THEN
Cabin = No	Driver = No
Driver = No	Remote operation: required
Remote operation: required	Cabin = Yes
Driver = Yes	Cabin = Yes
Vehicle type = Trailer mover	Operation speed = 15.0
Vehicle type = Terminal tractor	Operation speed = 30.0
Vehicle type = Tractor	Operation speed = 80.0
Vehicle type = Truck	Cabin = Yes
Vehicle type = Trailer mover	Cabin = No
Vehicle type = Trailer mover AND Autonomy level = Advanced	Cabin = Yes
Vehicle type = Trailer mover AND Autonomy level = Basic	Cabin = No
Remote operator = Full route	Ratio = 1:1
Remote operator = Section based	Ratio = 4:1
Remote operator = Situational	Ratio = 8:1
Remote operator = Exceptional	Ratio = 20:1

Table A.2 : Physical- and data infrastructure rules.

IF	THEN
Remote operation: required	Physical Control Room: required
Network sufficiency = Yes	System Cost = Free
Network sufficiency = No AND Network ownership = Public	System Cost = Low
Network sufficiency = No AND Network ownership = Semi-public	System Cost = Medium

IF	THEN
Network sufficiency = No AND Network ownership = Private	System Cost = High

Table A.3 : Integration logistics work processes rules.

IF	THEN
Level of integration = Level 0	Driver = Yes
Level of integration = Level 1	Driver = No
Level of integration = Level 1	Remote operator = Full route
Level of integration = Level 2	Driver = No
Level of integration = Level 2	Remote operator = Section based
Level of integration = Level 3	Driver = No
Level of integration = Level 3	Remote operator = Situational
Level of integration = Level 4	Driver = No
Level of integration = Level 4	Remote operator = Exceptional

Table A.4 : Traffic management rules.

IF	THEN
Interactions allowed = NO	Route = Dedicated lanes
Increased enforcement = NO	Remote operator = Section based

```
(model_entities:$terminal_tractor) isa required;
$cabin has available_type "YES";
$terminal_tractor has automation_tech_provider "FIXED_CHOICE";
$terminal_tractor has sensors "VEHICLE";
$terminal_tractor has navigation "GPS_HD_MAP";

$path_planning has path_planning_level "OD_FIXED";
$fall_back has fall_back_option "REMOTE_CONTROL";

$operational_domain has domain_type "YARD";

$terminal_layout has implement_changes "NO";
$physical_components has gate_option "AUTOMATED";
$physical_components has route "MIXED_TRAFFIC";
$physical_components has safety_measures "NONE";
$physical_components has sensor_control "NONE";
$physical_components has docks_stacks "AUTOMATED";

$security has availability_type "YES";
$connectivity has network_suffiency "NO";
$connectivity has network_type "SATELLITE";
$connectivity has network_ownership "PRIVATE";
$communication has communication_type "V2N";
$communication has communication_type "V2I";
$digital_systems has digital_maturity "PARTIALLY";

$traffic_priority has priority_rules "STANDARD";
$traffic_interaction has interactions_allowed "YES";
$traffic_interaction has diversity "HETEROGENEITY";
$chaotic_situations has increased_enforcement "NO";

$informing_road_users has information_type "NONE";
$driving has personnel "REMOTE_OPERATOR";
$un_loading has personnel "YARD_PERSONNEL";
$de_coupling has personnel "DRIVER";
$planning has personnel "HUMAN_PLANNER";

$lola has lola_level 2;

$value_chain_configuration has configuration "TRANSPORTERS";
```

Figure A.1: Input example of the CAT Requirements Database.

Component attribute list

	entity	attribute	block	value
0	terminal_tractor	sensors	vehicle_entities	VEHICLE
1	terminal_tractor	automation_tech_provider	vehicle_entities	FIXED_CHOICE
2	terminal_tractor	navigation	vehicle_entities	GPS_HD_MAP
3	terminal_tractor	operating_speed	vehicle_entities	30.0
4	cabin	available_type	vehicle_entities	YES
5	fall_back	fall_back_option	coordination_and_control_entities	REMOTE_CONTROL
6	driver	driver_type	coordination_and_control_entities	NO
7	path_planning	path_planning_level	coordination_and_control_entities	OD_FIXED
8	remote_operation	remote_operator_type	coordination_and_control_entities	SECTION_BASED
9	remote_operation	ratio	coordination_and_control_entities	0.25
10	terminal_layout	implement_changes	physical_infrastructure_entities	NO
11	operational_domain	domain_type	physical_infrastructure_entities	YARD
12	physical_components	sensor_control	physical_infrastructure_entities	NONE
13	physical_components	route	physical_infrastructure_entities	MIXED_TRAFFIC
14	physical_components	docks_stacks	physical_infrastructure_entities	AUTOMATED
15	physical_components	gate_option	physical_infrastructure_entities	MANNED
16	physical_components	safety_measures	physical_infrastructure_entities	NONE
17	control_room	needed	physical_infrastructure_entities	YES
18	digital_systems	digital_maturity	digital_infrastructure_entities	PARTIALLY
19	security	availability_type	digital_infrastructure_entities	YES
20	communication	communication_type	digital_infrastructure_entities	V2I
21	connectivity	network_ownership	digital_infrastructure_entities	PUBLIC
22	communication	communication_type	digital_infrastructure_entities	V2N
23	connectivity	network_suffiency	digital_infrastructure_entities	YES
24	connectivity	network_type	digital_infrastructure_entities	WIFI
25	connectivity	system_cost	digital_infrastructure_entities	Free
26	lola	lola_level	integration_logistics	2.0
27	value_chain_configuration	configuration	value_chain	TRANSPORTERS
28	ownership	execution_of_transport	value_chain	TRANSPORTER
29	ownership	digital_infra_ownership	value_chain	NETWORK_PROVIDER
30	ownership	vehicle_ownership	value_chain	TRANSPORTER
31	ownership	AV_logistics_interface_ownership	value_chain	AUTOMATION_PROVIDER
32	ownership	CT_ownership	value_chain	TRANSPORTER
33	ownership	planning_transport_ownership	value_chain	TRANSPORTER
34	traffic_interaction	interactions_allowed	traffic_management	YES
35	traffic_priority	priority_rules	traffic_management	STANDARD
36	traffic_interaction	diversity	traffic_management	HETEROGENEITY
37	informing_road_users	information_type	traffic_management	NONE
38	chaotic_situations	increased_enforcement	traffic_management	NO
39	un_loading	personnel	task_skills	YARD_PERSONNEL
40	de_coupling	personnel	task_skills	DRIVER
41	driving	personnel	task_skills	REMOTE_OPERATOR
42	planning	personnel	task_skills	HUMAN_PLANNER

Figure A.2: Output example of the CAT Requirements Database.

Appendix B
Overview assumptions

Table B.1: Financial assumptions.

	Value	Explanation	Source
Diesel Taxes	1000 euro per year	Diesel vehicles will have to pay taxes	Panteia TCO report [11]
Depreciation factor	0.23	See Panteia tool	Panteia TCO report [11]
Depreciation Period	7 years	Vehicles will be depreciated over 7 years.	Use cases
Rest Time factor	0.125	Personnel is assumed to work 7/8 of their hours, the rest is spent on breaks	Use cases
Effectiveness	0.88	Not all hours can be spent effectively, we assume 88%	Use cases
Labour cost factor	0.5	During the night hours, personnel gets paid 50% more	Use cases
Insurance factor	3.4%		Panteia TCO report [11]
Interest rate	4.23%		Panteia TCO report [11]

Table B.2: Vehicle purchase prices assumptions based on the State of the art analysis in CAT4Yards [8].

	Value []
Truck manned	Diesel: €125,000 Electric: €250,000
Truck autonomous (basic)	Diesel: €300,000 Electric: €350,000
Truck autonomous (advanced)	Diesel: €325,000 Electric: €420,000
Terminal tractor manned	Diesel: €100,000 Electric: €200,000
Terminal tractor autonomous (basic)	Diesel: €275,000
Terminal tractor autonomous (advanced)	Diesel: €300,000 Electric: €325,000
Trailer mover manned	Electric: €50,000
Trailer mover autonomous	Electric: €50,000

Table B.3: Vehicle variable maintenance assumptions.

	Value	Source
Diesel Truck	0.1 €/km	Use cases
Electric Truck	0.07 €/km	Use cases
Diesel Terminal tractor	0.05 €/km	Use cases
Electric Terminal tractor	0.05 €/km	Use cases
Electric trailer mover	0.02 €/km	Use cases

Table B.4: Vehicle fixed maintenance assumptions.

	Value	Source
Diesel Truck	2,300 €/year	Use cases
Electric Truck	1,500 €/year	Use cases
Diesel Terminal tractor	1,800 €/year	Use cases
Electric Terminal tractor	1,200 €/year	Use cases
Electric trailer mover	750 €/year	Use cases

Table B.5: Energy usage.

	Value	Source
Diesel Truck	0.3 L/km	[12]
Electric Truck	1.4 kWh/km	[12]
Diesel Terminal tractor	0.2 L/km	[13]
Electric Terminal tractor	1.0 kWh/km	[13]
Electric trailer mover	0.5 kWh/km	Estimation by expert interview

Table B.6: Energy usage stationary.

	Value	Source
Diesel Truck	1.5 L/h	[12]
Disel Terminal tractor	1.1 L/h	[13]

Table B.7: Variable Energy costs.

	Value	Source
Diesel	1.61 €/km	[11]
Electric	0.22 €/km	[11]

Table B.8: Yearly cost for Connectivity, Control Room and Adaptation of digital systems based on expert judgement.

	Value (Euros)
Small Control room	€20,000
Medium Control room	€30,000
Large Control room	€50,000
Low Connectivity	€3,000
Medium Connectivity	€7,500
High Connectivity	€10,000
Low System Cost	€5,000
Medium System Cost	€10,000
High System Cost	€15,000

Appendix C
Safety analysis

Table C.1: Complexity level with mitigation measures used in the safety analysis for a variety of topics.

Topic	Sub-topic	Low Complexity level	Medium Complexity level	High Complexity level	Mitigation measure to vehicle	Mitigation measure to surrounding
Communication / cyber	Proprietary protocol	Simple communication	Advanced communication	-	Try to keep it simple and proprietary	-
	Standard / Public protocol		Simple communication	Advanced communication	-	-
Localisation		Easy (no echoes from buildings, outdoors)	Moderate (Some echoes, indoor)	Hard (Many echoes, in-outdoor transitions)	Sensor fusion; Advanced algorithms for echo suppression; V2I communication	Use of absorptive material or scattering texture on parts of the environment; Reduce the number of 'problematic echo objects'; Sensors on infrastructure with V2I communication
Perception	Lighting Conditions	Fair weather	Bright low sun / Dark, with streetlamps	Dark, no streetlamps	Install additional lights on the vehicle, adjust sensor technology for object detection under complex lighting conditions; sensor fusion	Install additional lights on the terrain; reduce ODD by limited driving hours
	Weather Conditions	Mild rain / snow	Moderate rain / snow / fog	Heavy rain / snow / fog / sleet	Adapt sensor technology for wide range of weather conditions; sensor fusion	Provide covered driving lanes; reduce ODD by limiting driving conditions
Behaviour prediction	Impact loading conditions	No impact	Limited impact	Big impact	Detect load dimensions and center of mass and incorporate in trajectory planning	Create sufficient space for easy maneuvering
	Other road users – Qualification	None / Trained personnel	Informed visitors	General public	More advanced detection system, and behavior prediction and planning algorithms	Alternative trajectory; instruction for personnel and Visitors
	Other road users – Type	None / other ADS	Normal / Industrial vehicle	Cyclist / Pedestrian	More advanced behavior prediction and planning algorithms	Alternative trajectory; infrastructural changes (e.g., dedicated lane); traffic rules (e.g., right of way for ADS)

Topic	Sub-topic	Low Complexity level	Medium Complexity level	High Complexity level	Mitigation measure to vehicle	Mitigation measure to surrounding
	Other road users – Interaction	Some traffic crossings	Multiple traffic crossings / sharing road, no overtaking	Sharing road, with possible overtaking	More advanced behavior prediction and planning algorithms	Alternative trajectory; infrastructural changes (e.g., dedicated lane); traffic rules (e.g., right of way for ADS)
Traffic complexity	Markins and traffic signs	Clear / Standard	Proprietary / Chaotic	Absent / low quality	Train detection algorithm with location specific data; V2I Communication	Infrastructural changes: add or improve marking and traffic signs; standardize markings; V2I communication
	Special structures	None	Easily recognizable / protected (e.g. guarded railway crossing)	Difficult to recognize / unprotected	Train detection algorithm with location specific data; V2I Communication	Alternative trajectory, infrastructural changes; V2I communication
	Road type	Closed yard	Industrial Area	Non-Industrial Area	More advanced perception system, and behavior prediction and planning algorithms	Alternative trajectory
	Crossings / roundabouts	Easy (e.g. right turn / dedicated traffic lights / right of way)	Moderate (e.g. straight / general traffic lights)	Hard (e.g. left turn / no traffic lights / no right of way)	More advanced perception system, and behavior prediction and planning algorithms; V2I communication	Alternative trajectory; infrastructural changes (e.g., dedicated lane); traffic rules (e.g., right of way for ADS) sensors with V2I communication
	Max velocity difference	Small	Medium	Big	More advanced object avoidance (e.g. emergency braking, emergency maneuvers	Speed limit for all road users
Trajectory Planning		Simple (e.g. dedicated lanes / no special manoeuvres)	Moderate (e.g. standard roads / easy manoeuvres)	Complex (e.g. tight corners / challenging manoeuvres)	Improve vehicle maneuverability; more advanced planning algorithms	Alternative trajectory; infrastructural changes
Driving	Road surface quality	Good (smooth asphalt)	Medium (irregular / multiple surface types / some potholes)	Bad quality (many potholes)	More advanced position control; ESP; ESC	Regular road maintenance
	Road condition	Dry / Wet with good drainage	Wet with poor drainage (e.g. puddle forming)	Icy / Wet without drainage (many puddles / flooding)	More advanced position control; ESP; ESC	Regular road maintenance; protocols for extreme weather conditions

Appendix D
Workshop format logistics centered design approach CAT4Yards

This is a generic workshop format that can also be reused for other parties interested in CAT. Within CAT4Yards, we use this format as the starting point. Where necessary, adjustments can be made to ensure the outcome aligns well with the specific use case and any previous sessions that have taken place. The figure below shows the general steps that we follow in analysing the use cases. Generally, within 3 workshops all 3 phases of the Logistics Centred Design Approach Connected Automated can be covered.

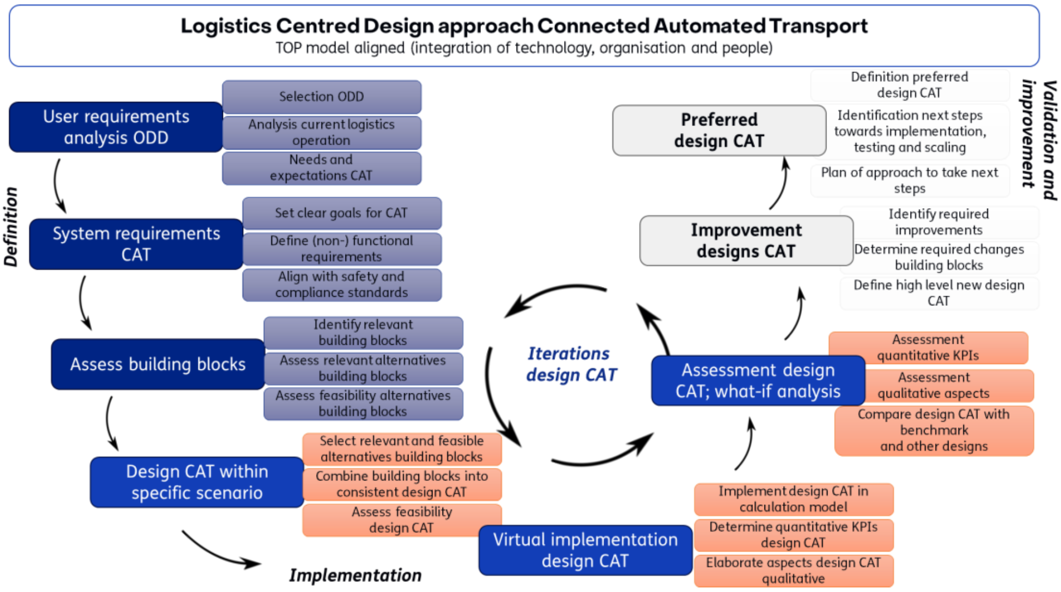

Figure D.1 Logistics Centred Design Approach Connected Automated Transport – detailed.

Session 1 - Definition phase
The goal of the first session is to map the current manned operation (AS-IS), gain understanding about the motivation for Connected Automated Transport and learn about the logistics organization system requirements and user preferences.

The estimated total duration of session 1 is 100-120 minutes.

Introduction – 15 minutes

Start with an introduction of all attendees, the aim of the different workshop sessions, the aim of today's session. The logistics company can shortly introduce their organization.

User requirements and current operation – 30-60 minutes

This is the main part of the session. The minimum required time to get a first understanding of current logistics processes and requirements regarding CAT is 30 minutes. However, it is advised to take more time here. Alternatively, one can hold an intermediate interview between session 1 and 2 to go into more detail. By the end of this part of the workshop one should understand the context of the current situation and assess the needs and expectation of logistics with respect to Connected Automated Transport.

	Discussion questions
Selection ODD	☐ What is the application area of CAT? Public road long-distance/ Industrial area/ Yard (private road)
Analysis current logistics operations	☐ Can you describe the current logistics process step-by-step? ☐ Can you provide a (satellite) map of the route? ☐ Are there any critical points on the route? ☐ Can you provide information on current operational parameters (see table below and Appendix E)?
Additional company information	☐ What are the labour costs per fte per hour? ☐ What is the depreciation period (number of years used to depreciate vehicles in the fleet)? ☐ What type of vehicles are in use? ☐ What digital infrastructure is in place? (Connectivity at the yard, logistic management systems, etc.).
Needs and expectations CAT	☐ What are the driving forces for the logistics organizations to explore opportunities of CAT? ☐ What are expected outcomes of CAT?

Table D.1: Operational input parameters per use case for the baseline (AS-IS).

Baseline	Remarks
Number of Manned vehicles	
Trips per day	
Distance per trip manned vehicle [km]	
Operating speed manned vehicle [km/h]	Average speed on use case trip (as is).
Maximum speed manned vehicle [km/h]	Maximum speed allowed on use case (as is)
Operational days per year	
Operation hours per day	
Operation hours during night	
Hourly labour cost driver [$]	
Manual handling time [min]	Time per trip whereby non-driving tasks are executed.
Number and type of personnel	Number of personnel required in the current as is case per personnel type (e.g. drivers)

CAT building blocks and System requirements – 30-45 min
This part of the session starts with a 15-minute presentation on the CAT building blocks to give an overview of relevant topics when integrating CAT in logistics processes at yards, to introduce the logistics company with Connected Automated Transport and the different design components. Subsequently the 15–30-minute discussion serves as a starting point for identifying system requirements for CAT.

	Discussion questions
Motivation CAT	☐ What is the motivation to start with CAT? ☐ What challenges does the organization face currently?
Requirements CAT*	☐ Are there any requirements/ boundary conditions with respect to current logistics processes and envisioned future? (Relate this in step to building blocks).
Alignment with safety and compliance standards	☐ What safety standards are currently in place? ☐ What compliance measures are currently in place?

* It there is time, the requirements can be explored in more detail through assessing the individual building blocks to more specifically identify whether there are non-negotiable starting points for the CAT design. If an organization has already clear ideas, make a qualitative description of the design and scenario(s) that need to be analysed. Make use of the building blocks below.

	Discussion questions
Assessing building blocks	☐ **Vehicle** – are there ex-ante already certain wishes for type of CAT vehicle? Concept like Trailer mover, terminal tractor, truck? Concept with or without cabin? ☐ **Coordination and control –** What preferences/ requirements are there with respect to control: remote operation or remote assistance? ☐ **Digital infrastructure –** What possibilities are there for (new) digital infrastructure investments? ☐ **Physical infrastructure** - To what extent are adjustments to physical infrastructure possible/ required/ not desired? ☐ **Logistics** work processes - To what extent are adjustments to logistics work processes possible/ required/ not desired? E.g. Certain tasks that a human operator is/ is not desired to do? ☐ Minimum and maximum operating hours? Are there any boundary conditions for 24/7 operation for example? ☐ **Traffic management** – What are preferences with respect to interaction between manned and unmanned vehicles? Any prioritization? ☐ **Tasks** of people – what type of personnel is required in the logistics processes? ☐ **Organization roles** - What roles are desired by the organization? Ownership of vehicles? Leasing of vehicles? What roles are desired for other stakeholders? ☐ Trust in other actors for data sharing (e.g. OEMs, automation providers, other …)

Session 2 Design & Feasibility

The goal of the second session is to start building the CAT designs (TO-BE), through iteratively reviewing the different CAT building blocks. And hence, this is the start of the implementation phase. In case session 1 already resulted in a first CAT-design, this session also reports back on the results of the analysis of that design.

The estimated total duration of session 2 is 100-120 minutes.

Introduction – 15 minutes
We start with a brief recap of the project objectives, the conceptual framework of the CAT buildings blocks and the steps of the Logistics Centred Design Approach. Then, we outline the goal for today's session.

Building Blocks Vehicle and Control – 20 minutes
We review the first four building blocks of the CAT building blocks framework (vehicle, coordination & control, physical infrastructure, digital infrastructure) using slides that summarize their scope and possible alternatives. The order of these building blocks is important because there are dependencies between them.

For each building block, there is time for a short explanation, questions, and discussion. To guide these discussions, specific questions help assess the building blocks, feasibility and qualitative KPIs. Time management is crucial for this first exploration.

Building block	Discussion questions
Vehicle	☐ Based on the vehicle archetypes, which features do you consider most critical for success? ☐ What is your opinion on the vehicles currently available on the market? Is there enough choice? ☐ How difficult is it to select a supplier and a vehicle, and why?
Coordination and Control	☐ How challenging is it to make decisions about a control tower, given that this is a completely new element in operations? ☐ How could the decision-making process for the control tower be made easier? ☐ Is it clear how a control tower can be purchased and set up? How could this be improved? ☐ How do you see the division of roles between the current Yard Management System (YMS) and a future control tower? ☐ To what extent would you like the control tower to automate decisions (e.g., assigning docks or trips)? ☐ How important is it to link the control tower to Roadnet (EU-wide data) so the yard is better aligned with hubs and depots?
Physical infrastructure	☐ Which areas of the yard do you currently see as most problematic or risky in terms of traffic and manoeuvring? ☐ Should the physical infrastructure remain the same? Is this a requirement? ☐ Or do you foresee other changes (e.g., separated traffic instead of mixed traffic)? ☐ Is it feasible to make these changes on your yard? ☐ How do you estimate the effort required to implement these changes?

	• Do you expect all changes to be implemented at once, or could this be phased? • What safety measures do you foresee, and how should the trade-off between safety and flexibility be managed? • How should current traffic rules (one-way traffic, speed limits, shunter priority) be adapted for autonomous vehicles?
Digital Infrastructure	• What does your current digital infrastructure look like? Is there a network in place? How strong is it? • How reliable is the current Wi-Fi coverage in practice on the yard (e.g., between trailers, at docks, or in “dark” zones)? • What are your main concerns regarding digital infrastructure? • Digitalizing processes is a major challenge—how far along are you in digitalizing your processes? • How do you plan to build resiliency into the process in case vehicle connectivity is lost? • How important is cybersecurity, and to what extent are you willing to pay extra for it? • Does your Yard and/or Transport Management software support autonomous driving? • What are your expectations of software vendors in supporting this change, and how well do your current vendors meet these expectations? • To what extent do you want to be responsible for the digital infrastructure (in-house or outsourced)?

Introduction to CAT4Yards Tooling and results of the first CAT Design – 30 minutes
We begin with a short introduction to the CAT requirements database tool and explain how the choices made within the building blocks on ‘Vehicle and Control’ are incorporated into the CAT design and the ex-ante impact assessment. By making use of an interactive dashboard we can present the results of TO-BE situation of CAT design 1.

Building Blocks 5 & 6 – 25 minutes
Based on the design decisions from the first four building blocks and the results of the initial analysis, we will now discuss the implications for the organization and ways of working. The changes required here are a consequence of earlier choices, but there may be contextual differences in the degree of change and the speed at which these changes need to be implemented.

For each building block, there will be time for discussion. Specific questions have been prepared to help validate the building blocks and assess feasibility and qualitative KPIs. Time management is essential—so not all questions need to be asked.

Building block	Discussion questions
Integration in Logistics	- Within which processes do you expect the biggest changes? → Yard (outside) - Within which processes do you expect the most complex changes? - Which processes today still rely heavily on human judgment (such as prioritization, handling exceptions, or visual checks)? - To what extent are adjustments to operating hours (peak/off-peak) interesting and feasible? - Are the processes inside (sorting hall) leading the processes outside (yard), or vice versa? - Do you expect all adjustments to be implemented at once, and how could a phased approach be possible? - To what extent does a phased approach pose a risk to the overall process? - How feasible do you think it is to temporarily run different processes in parallel? - How important is reliability (uptime) compared to cost savings?

Tasks of people	- Required skill sets and sourcing: What types of personnel and competencies are needed, and how will these be acquired?
	  o In which roles is automation most challenging?
	  o Which skills are hardest/easiest to find, and which roles should ideally be automated earlier or later because of that?
	  o Training and adaptation: How will personnel be trained for automated vehicle operations, and what impact will this have on other roles (e.g., yard operators)?
	- Do you expect resistance from staff? If yes, where do you expect the most resistance when automating tasks?
	  o Change management: How will staff be guided through this transition?
	- Organizational structure changes: Assess whether certain functions, such as a dedicated HR department, remain necessary.

Organization	- What role(s) do you want to be responsible for? (Vehicle ownership/ Digital infrastructure/ Transport planning/ Autonomous Vehicle-Logistics Interface/ Operating Control Tower/ Transport Execution)
	  o What factors are important for you when considering this? (e.g. being in control, outsourcing/ getting service/ remaining flexible)?
	  o To what extent does this differ from your current role?
	- What actors preferably are responsible for the remaining roles?
	  o Why? What is your reasoning?
	  o What considerations do you make when deciding on outsourcing? And is this different for CAT compared to other processes/assets?
	  o To what extent is collaborating with other transport companies in the region an option when acquiring autonomous vehicles?
	- Do you expect that roles may change over time? In what way? Would that be an opportunity or a threat to your position?

Alignment on Design 2 and 3 and closing – 10 minutes

To conclude, we will discuss the direction we want to take for developing Design 2 and 3. Which variations do we particularly want to explore, and within which building blocks?

Session 3 Alternative designs and improvement

CAT Design 2 Discussion and Adjustment – 30 minutes
Based on feedback and lessons learned from previous steps, we present and discuss the analyses for CAT Design 2. The goal is to give companies insight into the importance of certain choices and how these influence the design of the overall solution. During the discussion, parameters in the calculation can still be adjusted – making use of the dashboard - to gain more insight or to make the CAT designs better reflect expected reality.

Discussion Questions:

- What stands out in the results?
- What do you think should be the main cost components (not the amounts) of the overall solution, and does this align with the results?
- What are the key considerations and design choices that influence the total solution's cost?
- Which choices could potentially be made differently? And what is the impact on the calculation if we vary these parameters?
- Which uncertainties remain and should ideally be resolved?
- What are the most important criteria for evaluating a business case for fully autonomous driving?
- How realistic is it to create a business case for implementing fully autonomous driving based on this calculation?
- Flexibility gains from reducing reliance on unpredictable personnel
    - If personnel reliance decreases, what new opportunities do you see for reorganizing workflows or planning cycles?
    - Which tasks or processes could benefit from more predictable vehicle movements?
- Flexibility constraints introduced by CAT design choices
    - Can you describe scenarios where manual intervention is necessary today?
    - Which parts of your yard infrastructure are currently flexible or easy to adjust? Are there areas where you could imagine accepting less reversibility in exchange for higher operational efficiency or safety?
- Implementation effort –
    - Where do you expect the biggest differences between today's operation and the proposed CAT design?
    - Which of these changes do you consider minor adjustments, and which would be major shifts?
    - Are there areas where CAT integration would require completely new processes or roles?
    - Where might you need external support (e.g., IT integration, change management, training, infrastructure)?
    - Are there resource constraints that could slow down or complicate implementation?

CAT Design 3 Discussion and Adjustment – 30 minutes
Based on feedback and lessons learned from previous steps, we present and discuss the analyses for CAT Design 3. The goal is to give companies insight into the importance of certain choices and how these influence the design of the overall solution. During the discussion, parameters in the calculation can still be adjusted – making use of the dashboard - to gain more insight or to make the CAT designs better reflect expected reality.

Discussion Questions:

- What stands out in the results?
- What do you think should be the main cost components (not the amounts) of this solution, and does this align with the results?
- What are the key considerations and design choices that influence the total solution's cost?
- Which choices could potentially be made differently? And what is the impact on the calculation if we vary these parameters?
- How does this first step help reduce uncertainties? (see previous scenario answers)
- How does this first step help reduce risks related to the key criteria of a business case for the overall solution? (see previous scenario answers)
- What simplifications can be made in the design to limit investment while still gaining maximum insight into the consequences of introducing autonomous driving? (see previous scenario answers)
- Flexibility gains from reducing reliance on unpredictable personnel
  - If personnel reliance decreases, what new opportunities do you see for reorganizing workflows or planning cycles?
  - Which tasks or processes could benefit from more predictable vehicle movements?
- Flexibility constraints introduced by CAT design choices
  - Can you describe scenarios where manual intervention is necessary today?
  - Which parts of your yard infrastructure are currently flexible or easy to adjust? Are there areas where you could imagine accepting less reversibility in exchange for higher operational efficiency or safety?
- Implementation effort –
  - Where do you expect the biggest differences between today's operation and the proposed CAT design?
  - Which of these changes do you consider minor adjustments, and which would be major shifts?
  - Are there areas where CAT integration would require completely new processes or roles?
  - Where might you need external support (e.g., IT integration, change management, training, infrastructure)?
  - Are there resource constraints that could slow down or complicate implementation?

Discussion on Feasibility and Next Steps – 20 minutes

Based on the results, a final discussion will be held on the feasibility of the designs and how the company can now make decisions about next steps.

Discussion Questions:

- How has today's session contributed to insights and future decision-making regarding Connected Automated Transport?
- Where do you expect the biggest challenges in implementation?
- Where do you expect the greatest effort in implementation?
- Now that we have reviewed three CAT designs, what other designs do you see?
- What would an implementation plan look like that fits your business operations?
- To what extent do you expect to carry out this implementation yourselves, or will you need consultants/support?

Dashboard

To support the workshops, we make use of a dashboard. The dashboard supports in conducting what-if analyses. When analysing these results, the partner can decide which figures they would like to adjust to explore different outcomes. In most cases, this will simply mean rerunning the Impact Assessment. In some specific cases, it may also require adjustments in the CAT Design (CAT requirements database). This process can take place over several iterations until the outcomes are as realistic as possible.

The dashboard is used for the workshops with thus far Dutch use cases and is therefore written in Dutch. It consists of a frontpage as shown in Figure D.3. The front page has some general information about the current project, with an infographic on the most right. Furthermore, it explains the use case and introduces the different scenarios that are presented. Lastly, it gives an result of the TCO computations which shows the performance of the scenarios compared to both the diesel and electric baseline.

Figure D.2: Front page of the dashboard including general information and overview of TCO results.

The next tab of the dashboard consist of all general assumptions as described in Appendix B. These can be adjusted if requested by the user of the dashboard. Other tabs consist of scenario specific input and results. Figure D.3 represents such a scenario tab. On the most right hand side, the scenario specific operational input is given, which can also be adjusted for new iterations. On the left side, the graphs represent the Total TCO per year, the utilisation of the vehicles and the TCO per vehicle. Lastly, in the middle, other KPI results are summarised, among others the total required vehicles and operators, the total required personnel hours, emissions, total cost and utilisation.

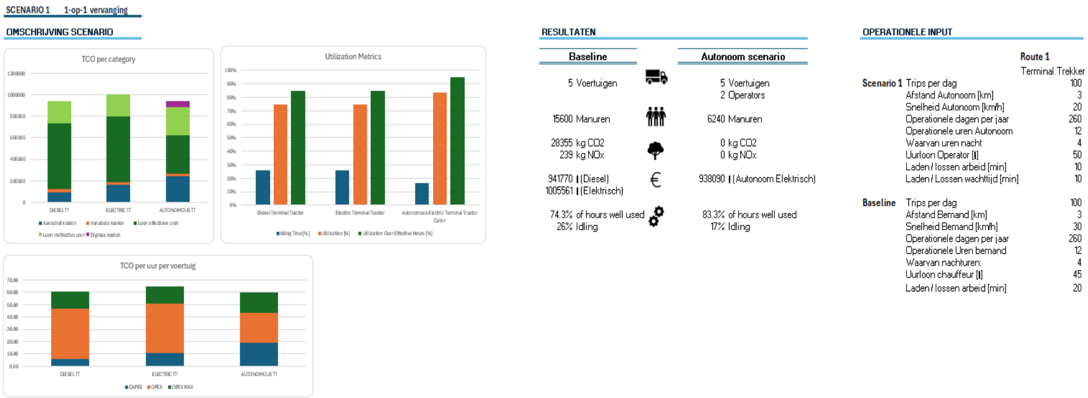

Figure D.3: Dashboard example output of scenario.

Appendix E
Data collection template

This appendix presents the data collection template used to gather the operational input required for each scenario within a given use case. The baseline scenario represents the AS-IS situation, reflecting current manned operations, while the autonomous scenario represents the TO-BE situation, reflecting future operations based on autonomous vehicle concepts.

For each scenario, input data must be provided for both the baseline and autonomous situations. Each scenario uses a single type of vehicle (e.g., terminal trekker, truck), and may include one or more routes. For each route, the required operational parameters are specified separately Table E.1. When multiple routes are included in a scenario, the overall costs and performance are calculated across all routes.

Table E.1: Operational input parameters per use case for the baseline (AS-IS) and autonomous (TO-BE) scenarios.

Autonomous scenario	Baseline
Autonomous vehicles	Manned vehicles
Trips per day	Trips per day
Distance autonomous vehicle [km]	Distance manned vehicle [km]
Speed autonomous vehicle [km/h]	Speed manned vehicle [km/h]
Operational days per year	Operational days per year
Operation hours per day	Operation hours per day
Operation hours during night	Operation hours during night
Hourly labour cost remote operator [$]	Hourly labour cost driver [$]
Manual handling time [min]	Manual handling time [min]
Automated handling time [min]	

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