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Toward a Morphological Chart of a Connected Autonomous Transport System for a Container Terminal

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Statement of Significance (Relevance of Research): This research advances the theoretical foundation by presenting a practical and comprehensive design approach for Connected and Autonomous Transport (CAT) systems. Using a morphological chart, this paper decomposes the complex elements of CAT systems into sub-functions, each offering multiple feasible options. By blending theoretical perspectives with practical insights, this study addresses a gap in literature, which has largely centered on vehicle autonomy functions, mathematical algorithms, and the broader benefits and impacts of autonomous vehicles**.**

The presentation will be of interest to TRB Meeting Attendees as it will help them to recognize the key elements of innovation and deployment projects for autonomous vehicles by various technology suppliers and logistics industry partners. In this phase, the number of different design parameters and options is enormous as most projects provide customized solutions. In the coming years, it is expected that dominant designs will emerge, but until then, the morphological chart will help attendees to identify and understand the differences between these designs and solutions.

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INTRODUCTION

In the Netherlands, the project SAVED (SAMENWERKEND AUTONOOM VERVOER OP BEDRIJVENTERREINEN) started to implement Connected and Autonomous Transport (CAT) system in XL Business Park, Twente. The project wants to apply CAT system in last-mile transportation which is judged to be an inefficient part of Supply Chain, especially in multimodal delivery. The CAT system is believed to bring a safer, more efficient, and cleaner transport solution and it could be the next revolution in road transportation. One target of SAVED project is to investigate the requirements that are needed to design and apply CAT system to the process of container movement in terminal. Thus, the changing role of humans, the new way of working between planner and CAT system, and shared ownership in that business model need to be concluded ahead [1]. This paper is the contribution of Rotterdam University of Applied Science as a research stakeholder in SAVED project. Relating to Work Package 1 (Design focused on vehicle and infrastructure), this paper aims to study design requirements to build a connected and autonomous transport (CAT) system.

One main reason for autonomous truck uprising is the truck driver shortage with high turnover recorded up to 39% after the Great Recession in 2010 [2] and hovered around 80%-92% since 2012 [3]. Moreover, driver-related costs occupy a large component of logistic companies' marginal costs. Those costs, including wages and benefits, take over 43% of the cost per mile and continue to be the biggest cost for motor carriers since 2014 [4]. Though driver's expenses are costly, last-mile businesses couldn't use up this resource because of high dependence on other steps in multimodal transportation. While logistics companies have to find solutions to keep their supply chain more cost-effective, flexible, and sustainable, autonomous transport is the key solution benefiting safety, economic, and environmental aspects. Although its potential benefits are foreseeable, there is limited research working on the overall system of autonomous trucks. There is a compelling need to research and make an all-inclusive information board to assist end-users in building their Connected and Autonomous transport (CAT) systems.

The research aims to develop a morphological chart of CAT system to assist project owners in terminals, business parks, and vehicle development companies planning to implement the CAT system. It helps developers customize CAT system designs to their specific circumstances by answering key questions arranged in the order of sub-functions in the chart.

METHODOLOGY

When studying a new topic with limited knowledge from existing literature, exploratory research is preferable. This type of research has qualitative and primary characteristics in its nature [5]. With the qualitative method, the paper relies more on text from academic papers, published articles, and interview transcripts. Although gathering multiple sources of data, the researcher is still the key instrument of this report with no reliance on any interview questions or instruments developed by others [6].

For empirical questions, this paper collected primary data in the form of interviews, mainly in virtual connections. Although interviewing gives unilateral points of view, this method allows the researcher to approach historical information of specific use cases [6]. Nowadays, with the popularity of video calls and recording techniques, virtual interview shows more advantages of saving time for both interviewer and participant, as well as surpassing all physical obstacles (e.g. travel time, travel cost,..). Most of the interview meetings were operated with Microsoft Teams application and they had an average duration of 60 minutes. The videos of virtual meetings were recorded with the permission of the interviewees for research purposes only. All interviews were conducted in a qualitative manner and semi-structured format, so there is room for follow-up questions based on the interviewees' content and expertises. The question list was prepared in advance and was used with no limits in any interview.

The interviewed participants work in different companies and institutions. This means collected data wouldn't be biased by the same case study or experience. Also, the interview answers only reflected the opinions of participants and would not represent the companies where they are working.

The interviewees are grouped by functional characteristics and clustered by category of being inside or outside of the SAVED project:

• Inside SAVED project: V-Tron, VDL, Bolk Transport, HAN UAS and Univesity of Twente

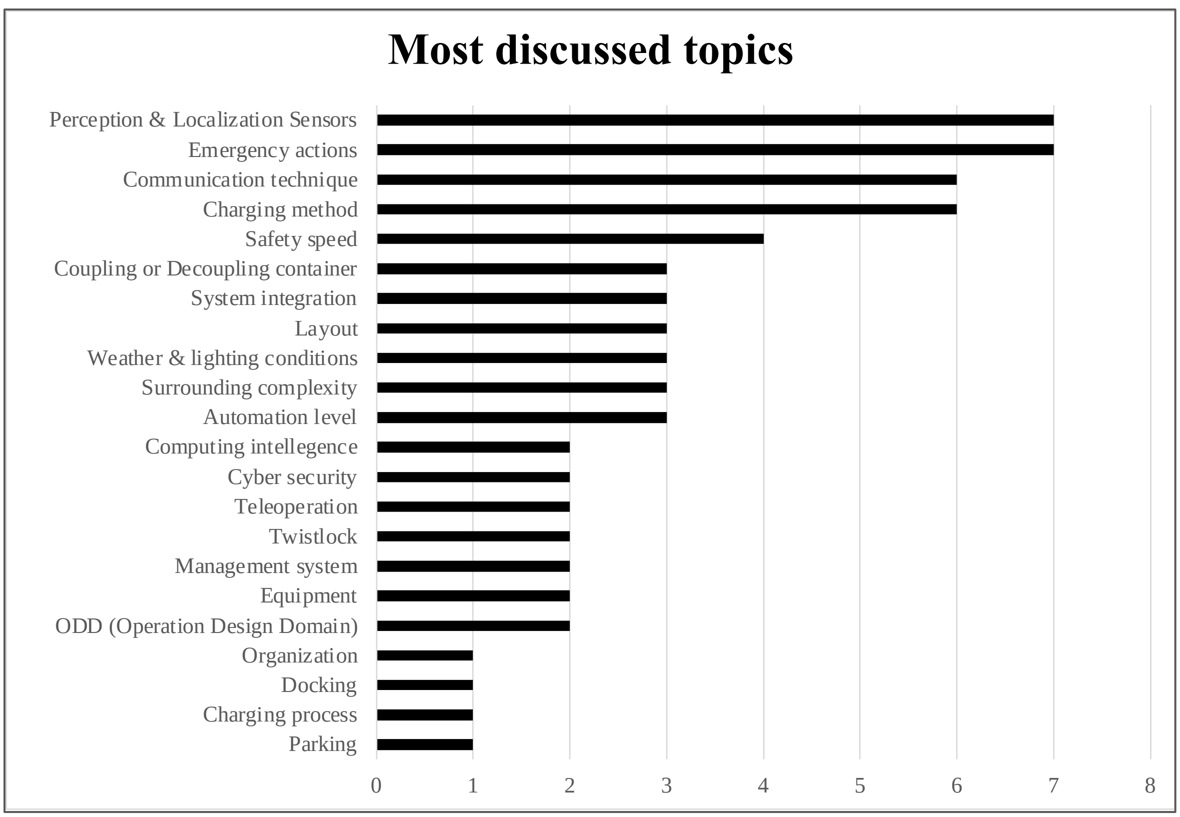
• Outside SAVED project: Easymile and APM Terminal, who had been piloting and developing autonomous trucks.

Besides, the researchers took advantage of the Terminal Operation Conference (TOC) Europe 2024 event, which was held in Rotterdam, Netherlands. This event took place in the middle of June 2024, with the main topics of port solutions and future potential developments, providing cutting-edge technologies and networking with leading companies. We approached several companies investing in autonomous transport innovation at the conference and discussed about autonomous truck systems at the terminal and the key functions they are developing. After that, each conversation was summarized and transferred to the researcher's notes. The companies were SYMEO, AIDrivers, Sumirai, Rochsys, WestWell and KALP.

RESULTS

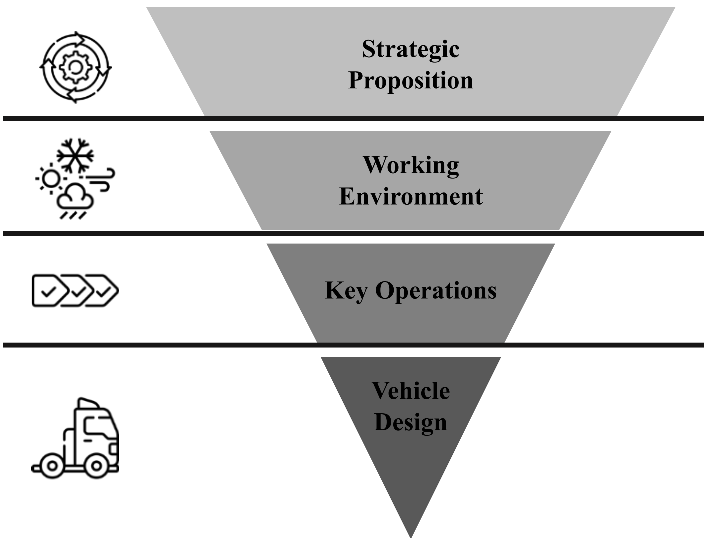
With the theoretical framework, formal interviews and informal discussions during the TOC event were taken, we conducted a summary of favorable topics. Figure 1 shows the most discussed topics; in which, vehicle sensors were focused mostly by experts to describe how an AV works and percepts the outer world. Equivalently, emergency actions were mentioned by seven participants because there are many concerns about the safety, reliability, and robustness of this new type of transportation. Many more topics were conversed about but there are only a few of them are reasonable to be organized in the selection basis to build up the morphological chart.

Figure 1. Most Discussed Topics During Interviews



Some first conversations focused only on vehicle design while neglecting the external working environment, which eventually turned out to be key decisional impacts on designing CAT system. Scope of work, environment conditions, and surrounding complexity considerably influence CAT system and logicalize how autonomous truck (AT) works and interacts. After transcribing and coding, frequent topics were organized to make a more logical order of sub-functions for the chart. Figure 2 shows the new hierarchical framework for designing CAT system, starting from Strategic Proposition to Working Environment, Key Operations, and Vehicle Design. In this framework, Vehicle Design is put as the last component, because every AT requires a standard fusion of sensors to ensure precision and reliability in surrounding situations. Thus, hybrid algorithm and hybrid communication technique are more favorable to adapt flexibility in operation. As a result, there is little room to alternate options in the design of an autonomous truck.

Figure 2. The Hierarchical Framework of CAT System



Finally, the morphological chart of CAT system is proposed in Figure 3, having four main components: Strategic Proposition, Working Environment, Key Operations, and Vehicle Design. Totally there are 16 sub-functions listed with two to four solutions per component. With this chart, end-user or researcher of CAT system could have a holistic idea about what and how CAT system could be made. Sub-functions of CAT system are elaborated and explained in Section 4.3.The final morphological chart of CAT system is proposed in Figure 3.

Figure 3. The Final Morphological Chart of CAT System

	Sub-functions	Options			
Strategic Proposition	Operational Design Domain (ODD)	Inside terminal	(+) Semi-public road	(+) Self-operating at destination	(+) Fullly public road
	Automation Level	Level 3	Level 4	Level 5	
Working Environment	Weather Conditions	Low frequency of extreme weather	High frequency of extreme weather		
	Lighting Conditions	Sufficient light	Insufficient light		
	Surrounding Complexity	Closed area	(+) Human-driven vehicles	(+) Pedestrians	
Key Operations	Check-in/check-out	Automated	Human interaction		
	Coupling & Decoupling	Automated	Human interaction		
	Twist Lock	Automated	Human interaction		
	Operating at Destination	Automated	Human interaction		
	Charging Process	Automated	Human interaction		
	Emergency Actions	Stand still	Move to emergency location	Teleoperation	
Vehicle Design	Perception Sensors	Sonar	Radar	LIDAR	Camera
	Localization Sensors	GNSS	IMU	Odometer	
	Communication Technique	Long-distance	Short-distance	Hybrid	
	Intelligent Perception	Centrailized	Decentralized	Hybrid	
	Charging Interface	Battery swapping	Plug-in charging	Induction	

CONCLUSIONS & DISUCCSION

The final morphological chart consists of four main components: Strategic Proposition, Working Environment, Key Operations, and Vehicle Design. Defining the *strategic proposition* for autonomous transport involves determining the Operational Design Domain (ODD) and automation level; they impact all subsequent decisions. The *working environment*'s weather and lighting conditions, along with the operational complexity involving human-driven vehicles and pedestrians, affect sensor settlement and safety measures. *Key Operations* include automating check-in/check-out, coupling/decoupling processes, docking processes, and emergency protocols like teleoperation. Communication strategies involve high bandwidth cellular networks like 5G for long-distance and V2X for short-distance communication with the support of Roadside Unit as a local computing service. *Vehicle design* mainly focuses on sensor fusion and selecting appropriate charging interfaces, balancing cost, and efficiency, with centralized and decentralized perception approaches.

The proposed morphological chart is designed to assist project owners in terminals, business parks, and vehicle development companies planning to implement the CAT system. It helps developers customize CAT system designs to their specific circumstances by answering key questions arranged in the order of sub-functions in the chart. For instance, questions include where autonomous trucks will operate, whether human supervision is needed, what the most extreme weather conditions are, what current lighting conditions are, etc. By systematically addressing these aspects, the chart aids end-users in decision-making, forming a combination of solutions for specific operational requirements.

This research contributes to the theoretical background by offering a practical and holistic design approach for Connected and Autonomous Transport (CAT) system. With the results of a morphological chart, this paper breaks down the complex components of CAT system into sub-functions, with multiple potential options. By integrating theoretical insights with practical experience, the research fills the gap in literature knowledge that mostly focuses on vehicle autonomous functions, mathematic algorithms, and benefits and impacts of autonomous vehicle, etc.

The research identified its limitations in geographical aspect when most of the interview participants and companies are in Netherlands. Hence, interviewees have separate expertise providing fragmented knowledge that make the researchers consolidate and summarize in personal perceptions.

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