EVS38
Göteborg, Sweden, June 15-18, 2025

Automation status and roadmap scenario for heavy duty road freight vehicles regarding different application scenarios

Robert Hahn[1,*], Samuel Hasselwander[1]
[1] *German Aerospace Center (DLR), Institute of Vehicle Concepts, Pfaffenwaldring 38-40, 70569 Stuttgart, Germany*
[*] *Corresponding author: robert.hahn@dlr.de*

Executive Summary

The automation of heavy-duty trucks (HDT) is advancing rapidly, with features like adaptive cruise control and emergency braking already standard. Companies such as Daimler Truck, Volvo, and Scania are testing highly automated functions up to SAE level 4, while fully driverless trucks are being trialed in pilot projects, especially on long-distance routes or within industrial zones (e.g. TuSimple, Einride). These varying stages of development make it difficult to estimate market entry timelines for automation in the various road haulage application scenarios (alt.: operational scenarios) like long-distance highway transport, hub-to-hub transport or urban delivery. This paper provides an overview of current HDT automation status and proposes a roadmap for different application scenarios based on the complexity of their characteristics. It highlights key pilot projects and aims to support logistics stakeholders in planning for implementation. The study finds that automation is more feasible with high motorway shares and becomes more complex with unsuitable loading and unloading operations.

Keywords: long haul road transport, heavy duty trucks, automation, scenario development

1 Introduction

Alongside the development of battery-electric and hydrogen-based drive options, the automation of road transport is one of the key areas of innovation in the mobility transition. Particularly in the field of HGTs, automated driving functions open up considerable potential for increasing efficiency, safety and sustainability in freight transport. In view of rising transport volumes, the growing shortage of drivers and ambitious climate targets, the question of practicable and economically viable application scenarios for automated HGTs is increasingly becoming the focus of industry, research and politics. Automated driving functions are now available in various degrees of maturity, and their implementation in logistics is increasingly seen as necessary to meet the challenges of modern transport.[1]

Automated driving technologies are currently at various stages of maturity - from assistance systems (level 1-2) to highly and fully automated solutions (level 4-5), which are already being tested in pilot projects. While certain applications, such as automated factory traffic in closed areas, are technically advanced, there are still significant challenges in other areas - such as urban delivery - in terms of sensor technology, decision-making logic, infrastructure connections and regulation.[2][3]

Against this background, the central research question arises: Which application scenarios - for example long haul highway transport, hub-to-hub connections, yard operations or urban delivery concepts - are most likely to be automated from a technological point of view? The aim of this paper is to provide a road map for the deployment-stages of HDTs in the most important application scenarios in long-distance road freight transport. To this end, the application scenarios are analyzed individually by breaking down their characteristics and evaluating their influence on the implementation of automation. It is meant to contribute to the prioritization of development strategies and investments in this dynamic area of technology.

2 Methodical Approach

The first step is to select the most frequently used HDT vehicle class. Based on the grouping of the Commission Regulation (EU) 2017/2400 (differentiated by axis configuration, chassis configuration and technically permissible maximum loading mass) this is the Long Haul, 4x2 tractor unit (LH-5). This class not only shows the highest annual mileage - which speaks in favor of long-distance use - but also one of the highest vehicle populations among all HDT classes.[4, p. 8]

As a second step, the most important application scenarios are determined. They provide information about the intended use and the operating environment of the HDT. The categorical subdivision and designation differ in the literature. The most commonly used application scenarios (in terms of turnover and daily operation) are listed in Table *1* with a brief description, based on Göckeler et al. [5, p. 39]. In the first column of Table *1*, the HDT application scenarios are clustered according to their individual characteristics. This is based on an analysis of the most relevant pilot projects in Europe and North America carried out to test autonomous heavy-duty single frame trucks and tractor unit lorries, shown in Figure 2.

Table 1: Cluster of the most relevant application scenarios according to Göckeler et al. [5]

Cluster of application scenarios	Application scenario	Description of the application scenario	Daily operation of the application profile in per cent	Share of company turnover in per cent
Hub-to-hub	Cargo transport	Goods are combined into load units and transported from the consignor to the consignee without being broken up. Wide range of 500-1000km.	82%	36%
Hub-to-hub	Collective transport / Concentricity	Goods (general cargo) from several consignors to different recipients. Transport in the main leg between two transshipment warehouses.	51%	19%
Hub-to-hub; urban	Delivery / collection	Individual delivery from the supplier to the customer.	47%	8%
Interurban	Transport of dangerous goods	High range requirements of up to 830 kilometers on average.	32%	8%
Terminal	Construction site traffic	Traffic flows within a construction site.	25%	9%
Terminal	Yard traffic	Freight transport with own company personnel. Routes mostly under 150km.	24%	5%
Interurban	Special / heavy transport	Transport of high range requirements of up to 725 kilometers on average.	15%	6%
Urban	Courier	courier express services (CES) transport mostly with smaller vehicle classes.	9%	3%
Urban	Assembly/customer service	Service trips to end customers, mostly with smaller vehicles.	-	1%
Urban	Moving transport	Transport of personal furniture and household goods.	-	1%
-	Other	Other transports	16%	4%

The complexity of the application scenarios with regard to the use of autonomous HDTs is assessed based on their individual characteristics. They are defined with the help of an evaluation matrix, so that any application scenario can be configured and evaluated through its characteristics for the use of autonomous HDTs. This makes the application scenarios comparable and allows for a rough scenario of market maturity based on the complexity for the use of autonomous HDTs in these scenarios. The weighting for the characteristics will be reviewed in a survey by a specialist group for autonomous driving. In the end, the scenarios for heavy duty autonomous driving can be sorted on a timeline regarding the technology readiness for market launch, leading to the final roadmap.

3 Results

As can be seen from the literature analysis (Figure *1*), most studies on roadmaps for fully autonomous driving show similar milestones from driving on the factory premises (yard operations) in the first step to platooning and highway pilots to hub-to-hub traffic with safety drivers and finally fully autonomous driving at SAE Level 5. In Figure 1, the estimates from the literature on the achievement of milestones are displayed on a timeline. This shows that most sources expect the Highway pilot and hub-to-hub transport by 2030. The timeframe for achieving fully autonomous driving for HDTs, on the other hand, is very long. This makes precise planning for the logistics sector difficult.

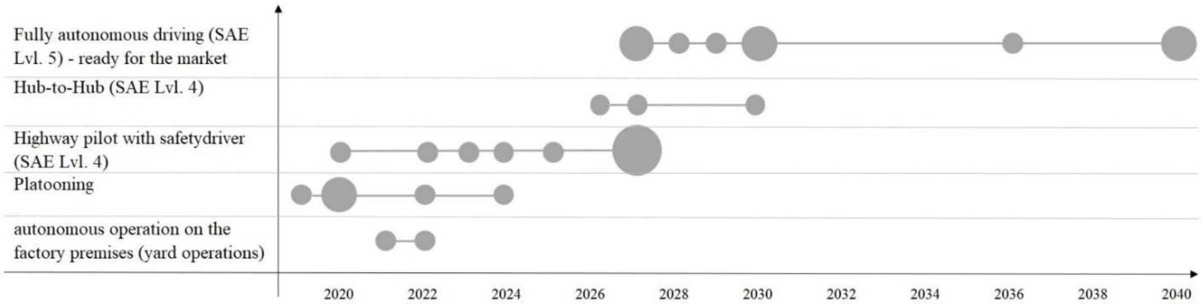

Figure 1: Milestone estimation in autonomous road freight transport (earliest milestone starting points based on sources from industry and literature) [6–20]

These roadmap-milestones can also be found in the already completed and ongoing pilot projects. More precisely, the projects can be divided into three different driving environments: terminal transport, highway-/interurban transport and hub-to-hub transport. A compilation of relevant projects is shown in Figure 2.

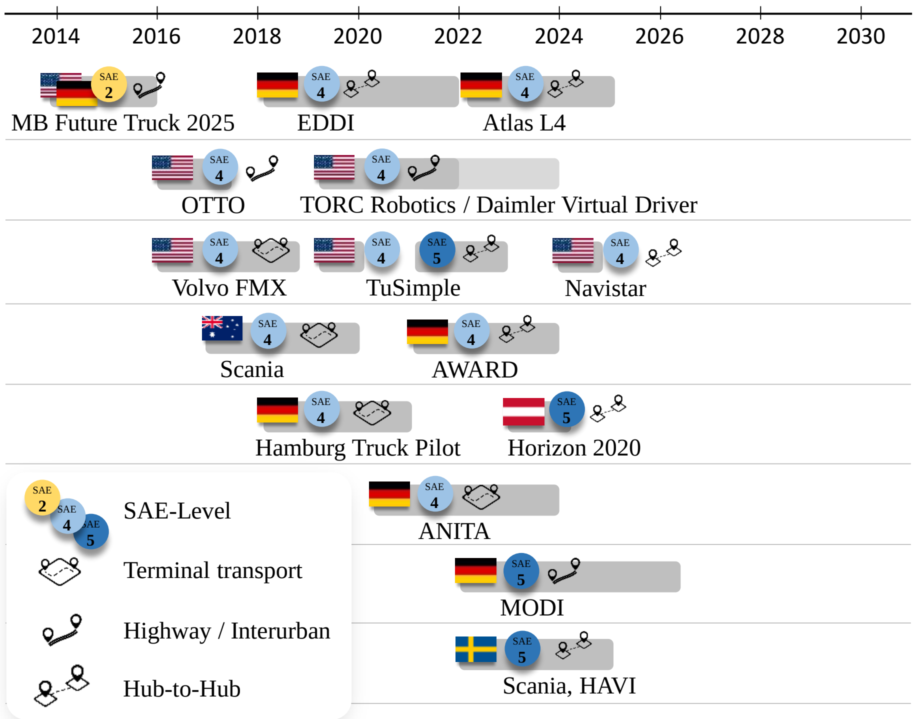

Figure 2: Major pilot projects for automated HDTs from 2014 to 2026

As seen in Figure 2, after testing in terminal transport and on factory premises, pilot projects will mainly take place on selected route sections or even in hub-to-hub transport. In contrast to terminal transport, the environmental conditions here are less controllable, which significantly increases the requirements for safety and situational awareness, as also stated from Hashimi et al. [13]. For this reason, almost all projects in public areas are still being carried out with safety drivers at SAE Level 4. These findings reflect in the application scenario characteristics which are analyzed in more detail. The characteristics were divided into the four main groups: infrastructure, transport task, traffic situation and environmental influences. Each character value has several options to describe the complexity it has on the operation model. Through an additional weighting for the relevance of each character value, they should be balanced with each other. The weighting of the values is to be determined and reviewed by automotive driving experts. All of the relevant characteristics as shown in Table *2*, known from the literature and research are recorded to describe the complexity of an operation model for the autonomous HDTs.

Table 2: The four main groups with associated relevant character values. Each character value is assigned several options that can be used to map the individual application scenarios.

Infrastructure	Transport task	Traffic situation	Situational awareness
Communication Car-to-X	Type of goods transported	Road users	Time of day / lighting conditions
Loading/refueling requirements during operation	Route length / journey	Traffic volume / density	Meteorology
Loading/unloading location	Loading and unloading processes	Direction of traffic flow	Weather extremes
Intervention options (control takeover)	Vehicle class (HDT-type)	Speed range	
Available infrastructure adaptations for autonomous driving	Delivery time window tolerance	Stationary traffic	
Emergency stopping options	Number of stops	Traffic disruption in case of system failure	

The individual character values reflect the current technical challenges for autonomous systems. The four core technologies according to Zhao et al. are the navigation system, route finding, environmental perception and the control system [21]. Ensuring safety is the top priority in all driving situations. It is primarily linked to the perception of the environment [22]. The more complex the situation and the greater the number of parameters to be considered by the autonomous system, the greater the challenge.

The simulation of the application scenarios with help of the character values confirms that the system complexity for autonomous driving is increasing, depending on the growing proportion of journeys in public traffic areas. In the roadmaps this is characterized through the shift from yard operations in a well controllable terminal to highway-only-trips with directional traffic to federal and city roads with crossing traffic. The complexity increases in particular due to higher demands on the environment perception caused by other road users, traffic rules and associated signal systems to be observed, as well as general traffic routing. This is reflected in the characteristics through higher requirement values in the "traffic situation" group (Table *2*) and also confirmed by Zhao et al.[21] and Saße and Willand [23]. The transport task is also becoming more complex with the switch to journeys in public traffic areas, due to longer transport distances or the loading and unloading points. These can vary greatly in terms of access, space conditions and maneuvering options, as well as available unloading aids and the need of manual work, as also noted by Csiszár and Földes [24].

Besides the traffic situation and transport task, the environmental parameters of weather, meteorology, time of year -and day have a particular impact on the complexity and safety because they can restrict the sensor system's field of vision. Cameras and lidar in particular have limited visibility in heavy rain, snowfall or fog. As even the high-precision maps only record the fixed infrastructure and not the road users, a solution for fully autonomous driving in poor visibility conditions is not yet within reach [25]. Communication, mainly Vehicle-to-everything (V2X) and vehicle-to-vehicle (V2V), is also often described as a challenging element, particularly due to network coverage, data protection, standardization and cybersecurity [26]. To communicate, connectivity is essential for the safe operation of vehicles [6, p. 5]. By networking vehicles with the infrastructure and other road users, the detection radius is extended beyond the field of vision of the detection sensors installed in the vehicle. This makes it possible to determine the position and status of signaling systems or road users at an early stage and further increases safety. Furthermore, it is very important for the system security that various intervention options, such as remote control of the HDT or available emergency stops, are available in the event of an emergency. This ensures that the vehicle does not interfere with surrounding traffic in the event of a system failure or emergency stop. The need to stop for refueling or charging especially on long-distance journeys also increases the complexity due to the access to the relevant refueling or charging station and the required manual assistance. It would therefore be best to use i.e. a fuel cell-power train that has a long range in order to avoid refueling stops on the road as far as possible and to refuel at the hubs.

Besides the already mentioned, further challenges can be found in non-technical areas such as legal matters, ethics, trust and acceptance, as well as business models [22]. The developed evaluation matrix enables a structured mapping and differentiation of various application scenarios for autonomous HDTs on the basis of defined character values. The comparison of the milestone scenarios for yard transport, hub-to-hub transport, and fully autonomous long-haul show a comprehensible increase in the operational complexity (Figure *3*). The reason for this is the greater complexity of the individual character values of the application scenarios. This observation is consistent with recent findings in the literature shown in Figure 1. In addition, the evaluation matrix also enables the comparative categorization of other, previously less investigated application scenarios and the systematic assessment of their respective complexity.

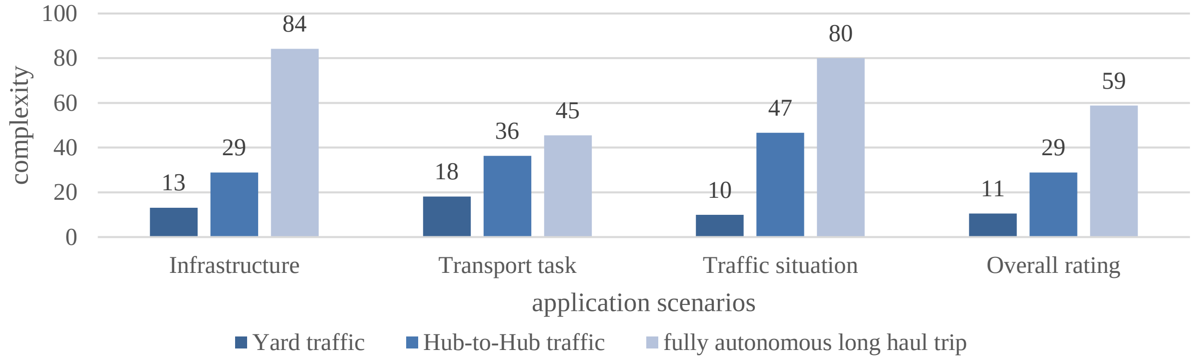

Figure 3: Comparison of the application scenario according to the defined character main groups on a percentage scale for complexity, created with the developed evaluation matrix. The character group for “situational awareness” was kept constant and therefor left out in these application scenario examples.

4 Conclusion

The findings show that the application scenario has a major influence on the degree of complexity in the use of autonomous HDTs and that this degree of complexity can be determined by the characteristics of the application scenario. As this can be directly translated into technical requirements such as environment and object recognition, route finding, autonomous maneuvering processes or system communication, the application scenarios can be roughly classified on a roadmap in terms of their potential development stage in the field of automation. This shows that certain application scenarios could enter automation earlier than others. As also shown in the pilot projects, the interface with the handover of goods is particularly challenging in terms of technical feasibility. The more decentralized this process is (away from logistics hubs), the more difficult it is to control the environment. The loading and unloading location, the load carrier and the available loading aids have a particularly large influence on the complexity. The previously high proportion of manual work in this area also makes it more difficult to implement the highest level of automation for decentralized transports, such as individual delivery scenarios in urban settings. In contrast, there are characteristics in the application scenarios that reduce complexity. These include, above all, a high proportion of motorways and loading and unloading in controllable environments such as terminals or hubs. A possible time estimate for automation in the mentioned milestone scenarios is shown in Figure 4. In future research, the character values of the application scenarios should be further detailed with the help of experts in order to be able to better assess the effects of technological developments.

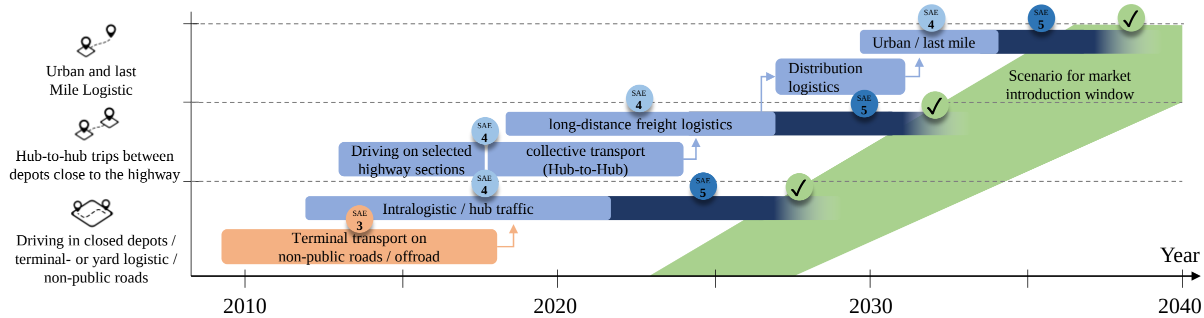

Figure 4: Roadmap scenario of milestones for autonomous HDTs based on the application scenario complexity analysis. The colors represent the SAE-Levels divided in two development steps for Level 4 with safety driver and Level 5 for full autonomous driving.

References

[1] B. Sen, M. Kucukvar, N. C. Onat, and O. Tatari, "Life cycle sustainability assessment of autonomous heavy-duty trucks," *J of Industrial Ecology*, vol. 24, no. 1, pp. 149–164, 2020, doi: 10.1111/jiec.12964.

[2] A. Mohan and P. Vaishnav, "Impact of automation on long haul trucking operator-hours in the United States," *Humanit Soc Sci Commun*, vol. 9, no. 1, 2022, doi: 10.1057/s41599-022-01103-w.

[3] S. Lee, K. Cho, H. Park, and D. Cho, "Cost-Effectiveness of Introducing Autonomous Trucks: From the Perspective of the Total Cost of Operation in Logistics," *Applied Sciences*, vol. 13, no. 18, p. 10467, 2023, doi: 10.3390/app131810467.

[4] KBA, "Verkehr in Kilometern - Inländerfahrleistung (VK): Entwicklung der Fahrleistungen nach Fahrzeugarten," Accessed: Apr. 7 2025. [Online]. Available: https://www.kba.de/DE/Statistik/Kraftverkehr/VerkehrKilometer/vk_inlaenderfahrleistung/2023/verkehr_in_kilometern_kurzbericht_pdf.pdf?__blob=publicationFile&v=3

[5] K. Göckeler, F. Hacker, and L. Ziegler, "Anforderungen der Logistikbranche an einen Umstieg auf klimaschonende Fahrzeugtechnologien: Ergebnisbericht einer standardisierten Befragung," Berlin, 2022. Accessed: 05/2024. [Online]. Available: https://www.oeko.de/fileadmin/oekodoc/StratES-Teilbericht_2-Befragung_Logistikbranche.pdf

[6] D. Gruyer, O. Orfila, S. Glaser, A. Hedhli, N. Hautière, and A. Rakotonirainy, "Are Connected and Automated Vehicles the Silver Bullet for Future Transportation Challenges? Benefits and Weaknesses on Safety, Consumption, and Traffic Congestion," *Front. Sustain. Cities*, vol. 2, 2021, doi: 10.3389/frsc.2020.607054.

[7] Traton, *Autonomous trucks: a reality as early as 2030?* [Online]. Available: https://traton.com/en/newsroom/current-topics/autonomous-trucks-a-reality-as-early-as-2030.html (accessed: Apr. 7 2025).

[8] ACEA, *AUTOMATED AND AUTONOMOUS DRIVING.* [Online]. Available: https://www.acea.auto/files/ACEA_Automated_and_autonomous_roadmap.pdf (accessed: Apr. 7 2025).

[9] Ryan, *Intelligent Mobility is Shaping the Future of Automotive Technology.* [Online]. Available: https://funding.ryan.com/blog/business-strategy/intelligent-mobility-automotive-technology/?utm_source=mentorworks.ca&utm_medium=referral&utm_campaign=redirect (accessed: Apr. 7 2025).

[10] Roadtoautonomy, *Daimler Truck Unveils Ambitious Autonomous Truck Strategy.* [Online]. Available: https://www.roadtoautonomy.com/daimler-truck-autonomous-truck-strategy/#:~:text=Between%202025%20and%202030%2C%20Daimler,autonomous%20trucks%20to%20the%20market. (accessed: Apr. 7 2025).

[11] C. Nallinger, *Digitalisierung setzt Lkw-Bauer unter Druck.* [Online]. Available: https://www.eurotransport.de/logistik/it-und-telematik/studie-von-oliver-wyman-sieht-handlungsbedarf-digitalisierung-setzt-lkw-hersteller-unter-druck/ (accessed: Apr. 7 2025).

[12] A. Kelkar, K. Heineke, M. Kellner, and T. Möller, *Will autonomy usher in the future of truck freight transportation?* [Online]. Available: https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/will-autonomy-usher-in-the-future-of-truck-freight-transportation (accessed: Apr. 7 2025).

[13] L. Hashimy, L. Colais, and F. Rosinés, "Roadmap towards connected and automated heavy-duty vehicles for logistics operations," 2024. Accessed: Apr. 7 2025. [Online]. Available: https://www.ccam.eu/wp-content/uploads/2024/09/101006817_Deliverable_46_Roadmap-towards-connected-and-automated-heavy-duty-vehicles-for-logistics-operations.pdf

[14] H. Günther, N. Harish, and T. Karl, *Will Level 4 hub-to-hub concepts transform the road transport market?* [Online]. Available: https://www.linkedin.com/pulse/level-4-hub-to-hub-concepts-transform-road-transport-market-g%C3%BCthner (accessed: Apr. 7 2025).

[15] S. Clevenger, *Torc Lays Out Road Map to Autonomous Truck Launch in 2027.* [Online]. Available: https://www.ttnews.com/articles/torc-autonomous-launch-27 (accessed: Apr. 7 2025).

[16] Continental, *Autonomous Trucks with High-tech Power from Continental.* [Online]. Available: https://www.continental.com/en/products-and-innovation/innovation/automated-driving/autonomous-truck/ (accessed: Apr. 4 2025).

[17] ERTRAC, "Automated Driving Roadmap," 2015. Accessed: 10/2024. [Online]. Available: https://www.ertrac.org/wp-content/uploads/2022/07/ERTRAC_Automated-Driving-2015.pdf

[18] F. Enzian, *MAN’s roadmap to 2030.* [Online]. Available: https://www.man.eu/corporate/en/experience/mans-full-commitment-to-autonomous-trucks-120256.html (accessed: 10/2024).

[19] T. Chafekar, "A Systems Analysis and Technology Roadmap for Autonomous Long-Haul Cargo Transport," 2021. Accessed: Apr. 7 2025. [Online]. Available: https://dspace.mit.edu/bitstream/handle/1721.1/139167/chafekar-tchafekar-sm-sdm-2021-thesis.pdf?sequence=1&isAllowed=y

[20] M. Blouin, *Autonomous Trucks Roadmap.* [Online]. Available: https://thepitgroup.com/autonomous-trucks-roadmap/ (accessed: Apr. 7 2025).

[21] J. Zhao, B. Liang, and Q. Chen, "The key technology toward the self-driving car," *IJIUS*, vol. 6, no. 1, pp. 2–20, 2018, doi: 10.1108/IJIUS-08-2017-0008.

[22] D. Kim, R. R. L. Mendoza, K. F. R. Chua, M. A. A. Chavez, R. S. Concepcion, and R. R. P. Vicerra, "A Systematic Analysis on the Trends and Challenges in Autonomous Vehicles and the Proposed Solutions for Level 5 Automation," in *2021 IEEE 13th International Conference on Humanoid, Nanotechnology, Information Technology, Communication and Control, Environment, and Management (HNICEM)*, Manila, Philippines, 2021, pp. 1–6. [Online]. Available: https://ieeexplore.ieee.org/document/9731982/authors#authors

[23] J. Saße and M. Willand, *Autonomes Fahren kommt am ehesten in der Logistik.* Accessed: Oct. 29 2024. [Online]. Available: https://edison.media/verkehr/autonomes-fahren-kommt-am-ehesten-in-der-logistik/25237132/

[24] C. Csiszár and D. Földes, "System Model for Autonomous Road Freight Transportation," *PROMET*, vol. 30, no. 1, pp. 93–103, 2018, doi: 10.7307/ptt.v30i1.2566.

[25] M. A. Khan *et al.*, "Level-5 Autonomous Driving—Are We There Yet? A Review of Research Literature," *ACM Comput. Surv.*, vol. 55, no. 2, pp. 1–38, 2023, doi: 10.1145/3485767.

[26] X. Yang, Y. Shi, J. Xing, and Z. Liu, "Autonomous driving under V2X environment: state-of-the-art survey and challenges," *Intelligent Transportation Infrastructure*, vol. 1, 2022, doi: 10.1093/iti/liac020.

Presenter Biography

Robert Hahn (M.Sc.) is working as a research assistant at the DLR Institute of Vehicle Concepts since 2017 in the areas of concept development, design and requirements analysis.
Mr. Hahn studied Industrial Design at the University of Applied Sciences Magdeburg from 2010 to 2014. During this time, he gained professional experience at various companies in the automotive industry, including Mercedes-Benz, Volkswagen in Mexico and Nissan in Japan. He finished his second bachelor's degree in Transportation Design at the University Pforzheim in 2017. In 2023, he completed a two-year, master's degree in management and engineering at the University Pforzheim with a thesis for Porsche.

Samuel Hasselwander holds a Master's degree in Mechanical Engineering from the University of Stuttgart and is currently working at the Institute of Vehicle Concepts of the German Aerospace Center (DLR). For more than four years, he has been evaluating vehicle propulsion technologies for future passenger cars, focusing on hybridized and fully-electrified systems, as well as synthetic fuels. Additionally, he plays an integral role in the analysis of vehicle technology scenarios within the context of climate change, particularly in terms of different cell chemistries, energy efficiency, and the sustainability of future vehicles.