Measuring Efficiency of Automated Road Freight Transport: The AWARD Approach

Matthias Neubauer[1], Wolfgang Schildorfer[1], Manuel Walch[1],
Sami Koskinen[2], and Loha Hashimy[3]

1. University of Applied Sciences Upper Austria, Steyr, Austria
2. VTT, Tampere, Finland
3. Enide, Barcelona, Spain

Corresponding author: matthias.neubauer@fh-steyr.at

Abstract: *Autonomous vehicles will be a key ingredient of future road transport solutions. Even if significant progress has been made in technological developments and autonomous transport vehicle demonstrations, there are still challenges to be addressed before widespread adoption can occur, e.g., 24/7 availability in harsh weather conditions. Quantifying the performance of autonomous vehicles is crucial for logistics operators when deploying such solutions. This paper presents KPIs related to autonomous road freight transport. Furthermore, the evaluation methodology of the European H2020 project AWARD related to efficiency of autonomous vehicles is presented and initial insights from the project are sketched.*

Keywords: *L4 autonomous freight transport, vehicle efficiency, fleet management efficiency*

Conference Topic(s): *Autonomous systems and logistics operations (robotic process automation, autonomous transport/drones/AGVs/swarms); ports, airports and hubs; vehicles and transshipment technologies.*

Physical Internet Roadmap *(Link): ☒ PI Nodes, ☒ PI Networks, ☐ System of Logistics Networks, ☐ Access and Adoption, ☐ Governance.*

1 Introduction

Logistics services represent a fundamental element of today's economic activities. The last decades have demanded for continuously improving logistics performance. A number of challenges, such as the Corona-Pandemic, labor shortages, ambitious sustainability goals, digitalization or increasing freight volumes have put pressure on logistics service providers to optimize their performance. One potential solution to these challenges is the use of autonomous road transport vehicles.

Autonomous vehicles have the potential to address key issues in commercial transportation, such as the lack of qualified drivers, the number of fatal accidents with trucks, or 24/7 transportation. Significant progress has been made in the field of autonomous road freight transport with numerous prototypes on the road in Europe and North America. Companies like KAMAG in Germany and TuSimple in US have successfully demonstrated their prototype vehicles in commercial operation with key logistic companies such as DB Schenker and US Postal, respectively. However, there are still challenges to be addressed before widespread adoption can occur. From a technological point of view, the deployment of autonomous heavy-duty vehicles is hindered by the current inabilities of these vehicles to work with the right safety and functional level for 24/7 availability (e.g., in harsh weather conditions, dense fog, heavy rain or snow). This is a crucial pain point, as the majority of users are operating time critical logistic flows, they must have the certainty that autonomous trucks will deliver an agreed throughput with agreed timing to integrate them in their logistic processes.

Quantifying the performance of autonomous road freight transport vehicles is crucial to be able to take informed decisions when it comes to the deployment and continuous improvement of them. This research paper derives performance indicators for autonomous road freight transport from related work. Furthermore, the paper illustrates the respective efficiency evaluation methodology designed in the EU-H2020 project AWARD (All Weather Autonomous Real logistics operations and Demonstrations) and sketches initial evaluation findings. The presented performance indicators comprise the evaluation aspects (i) fleet efficiency, (ii) vehicle efficiency, and (iii) the efficiency of handling of goods which may be affected by autonomous road freight transport. For these evaluation aspects, initial results related to differences between manual und autonomous operations will be sketched.

This research paper is structured as follows. Following the introduction, related work addressing performance indicators relevant for the efficiency of autonomous road freight transport is presented. Based on the related work, the evaluation methodology designed within the H2020 project AWARD is presented and initial results are sketched. This research paper concludes with a result discussion and an outlook on future work.

2 Related Work

Efficiency is a key ingredient of business success within the logistics domain. As such monitoring and improving efficiency represents an important logistics activity. Subsequently, related work regarding the measurement of transport efficiency as well efficiency measurement of autonomous transport vehicles is presented.

Andrejić et al. (2016) review related work on measuring transport efficiency and they distinguish between two basic aspects of measuring transport efficiency, i.e., (i) fleet efficiency and (ii) vehicle efficiency. Performance indicators for vehicle efficiency refer to the vehicle itself and may comprise, e.g., fuel consumption, vehicle emissions, vehicle range, vehicle capacity, or insurance costs. Fleet efficiency targets a higher decision level and aims at optimizing the management of a vehicle fleet to perform transport task. Today, IT systems (fleet management systems) support transport logistics providers in this endeavor. The subsequent Table 1 adapts the literature review from Andrejić et al. (2016) and summarizes measures related to transport efficiency within the categories (1) vehicle efficiency and (2) fleet efficiency. In general, vehicle efficiency indicators can be classified to operational indicators (e.g., fuel consumption, vehicle capacity, driving distance, emissions, etc.), financial indicators (e.g., labor costs, insurance costs, fuel costs, etc.), and quality related indicators (e.g., quality delays). The same categorization can be applied for fleet management efficiency indicators, Thereby, operational indicators are for example total number of trucks, total capacity, average load factor of trucks, total fleet fuel consumption, total fleet emissions, etc. Financial indicators for fleet efficiency are e.g., total wages, total fuel costs, total insurance costs, etc. Quality indicators for fleet management could be total number of transport failures.

Table 1: Transport efficiency indicators review. Adapted from Andrejić et al. (2016)

Publication	Vehicle efficiency indicators	Fleet efficiency indicators
Andrejić et al. (2016)	Fuel consumption (l), number of stops (deliveries), distance driven (km), number of shipped pallets	Number of vehicles, fuel costs, total truck operating time (h), distance driven (km), shipped tons(t), vehicle utilization (%)
Andrejić et al. (2013)	Fuel consumption (l), vehicle maintenance costs, shipped pallets, distance driven (km), number of stops (deliveries)	Number of vehicles, number of employees in transport, fuel costs, invoices (demands), driver's overtime, driver's overtime per driver, tour/driver, delivery/driver, tons/ driver, pallets/driver, distance/driver, time truck utilization, space truck utilization, failures in transport
Cruijssen et al. (2010)		Equipment (e.g., number of trucks, number of trailers, total loading capacity etc.), labor (e.g., total wages, (drivers') experience, total hours worked, number of employees, etc.)
van Donselaar et al. (1998)	Direct cost/truck, wages/driver, hours/truck, hours/driver, speed, (un)loading time/trip, turnover/trip, loading capacity, variable costs/km	km/truck (km/trip & number of trips/truck), load factor when not empty, % km driven empty, turnover / (1000 kg*km)
Kim (2010)	Labor cost, fuel cost, oil cost, supplies cost, taxes/insurances/etc., transportation distance, transportation amount, transportation distance	Average efficiency (%), no. of efficient trucks, efficient trucks (%), minimum efficiency (%)
Kuosmanen and Kortelainen (2005)	Mileage, fuel consumption, undesirable outputs (CO2, CH4, N2O, CO, NOx SO2, emissions…)	
Simons et al. (2004)	Labor, energy consumption, operating costs, vehicle emissions, fuel, transport losses or wastes (driver breaks, excess loading time, fill loss, speed loss, quality delay)	

In the field of autonomous transport vehicles, Innamaa and Kuisma (2018) present results of a survey with 77 expert for the impacts of automation in road transportation. They define overall twelve impact areas of automation and investigate related key performance indicators. With respect to efficiency, especially the areas (i) vehicle operations / automated vehicles, (ii) use of automated driving, (iii) energy or environment, and (iv) costs present relevant indicators from the automation domain. Following, the top 3 ranked KPIs for each area are listed in Table 2.

Table 2: Top 3 KPIs for assessing the impacts of automation in road transportation. Adapted from Innamaa and Kuisma (2018)

Area	KPI
Vehicle operations	# instances where driver must take control per 1000km
	Mean and max duration of the transfer of control between operator/driver and vehicle (when requested by the vehicle)
	Mean and max duration of the transfer of control between operator/driver and vehicle (in case of manually overruling on/off)
Use of automated driving	# instances where driver must take control per 1000km
	Use of automated driving functions (% of km of maximum possible use)
	Comprehensibility of user interface (expressed on a Likert scale, e.g. 1–9, low–high)
Energy or environment	Energy consumption of a vehicle (liters / 100 km or miles per gallon or electric equivalent)
	Tailpipe carbon dioxide (CO2) emissions in total per year and per vehicle-km or -mile
	Tailpipe criteria pollutant emissions (NOX, CO, PM10, PM2.5, VOC) in total per year and per vehicle-km or -mile
Costs	Capital cost per vehicle for the deployed system (infrastructure, monetary value)
	Cost of purchased automated vehicle (market price, monetary value)
	Operating cost for the deployed system (per vehicle-hour or per vehicle-km or mile, monetary value)

The fleet efficiency, as investigated in related work of transport efficiency, is not explicitly defined as KPI-area by Innamaa and Kuisma (2018). However, further KPI-areas such as safety, personal mobility, travel behavior (modal share, distribution on routes, etc.), network efficiency, asset management (physical and digital infrastructure), public health, land use, and economic impacts are investigated by the authors. These areas define KPIs either on a generic level or out of scope of measuring efficiency of automated road freight transport.

3 AWARD Efficiency Measurement Approach

3.1 AWARD Overall Testing and Evaluation Methodology

In terms of the overall testing and evaluation methodology, the AWARD project (see AWARD project (2023)) adopts the FESTA handbook (see ARCADE Project (2021)). The Handbook was originally produced by the Field opErational teSt supporT Action (FESTA) in 2008. The handbook aimed at guiding upcoming automotive field operational tests and a new wave of EU projects. Since then, the handbook has been repeatedly updated by follow-up networking projects, collecting lessons learned (e.g., from FOT-Net, CARTRE and ARCADE). The FESTA handbook mainly targets large-scale user tests, but in recent years it has been successfully applied in various smaller testing campaigns, as well. A core contribution of the handbook is the FESTA V, which is the procedural model for guiding the conduction of Field Operational Tests (FOTs). Figure 1 depicts the proposed steps to be taken within the FESTA V application.

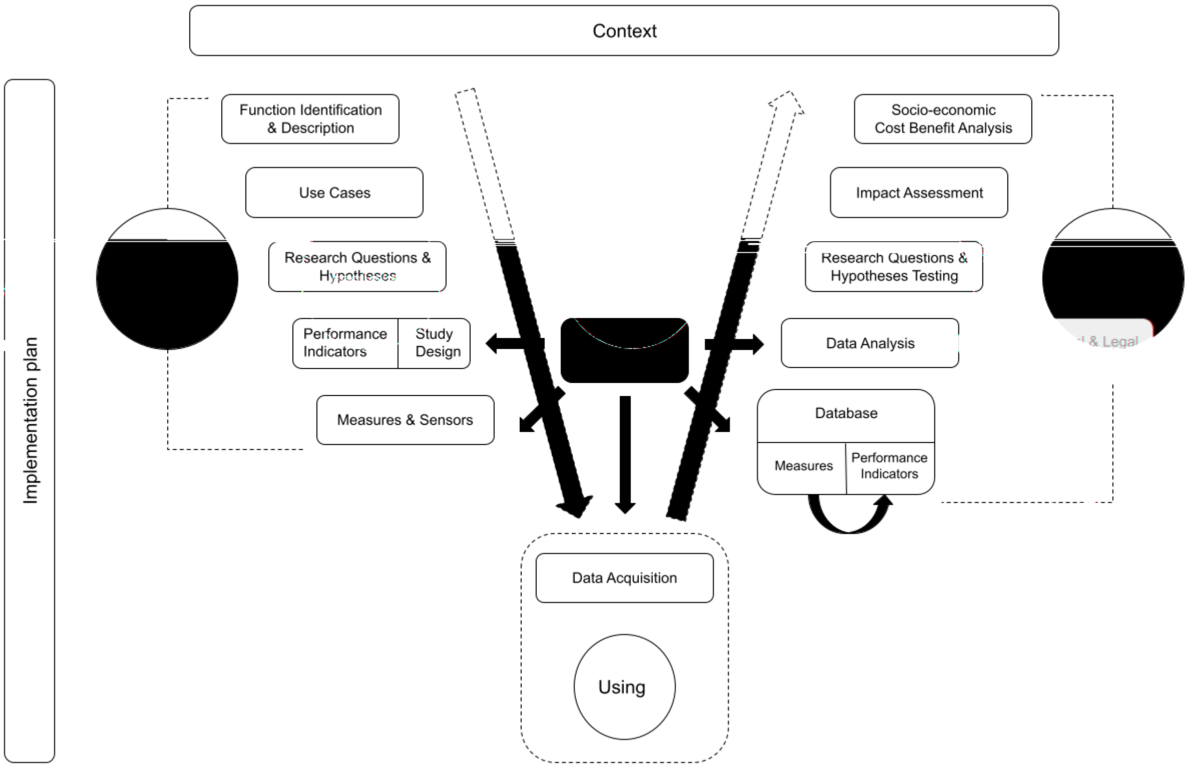

Figure 1: FESTA V - procedural model for field operational tests. Adapted from ARCADE Project (2021)

The first project year targeted evaluation preparations covered the left side of the FESTA V. As in FESTA, the main topics in the beginning of a study are to scope research questions and work towards an agreed focus and data to be collected. Tests and data collections have to be planned from the perspective of statistical evaluation – commonly this means collecting enough data both with and without the tested system in use. In addition to the operative tests in the final project year, the AWARD project has performed earlier testing related to product development and safety validation. Before the operative tests can begin, a certain amount of pre-testing and fine tuning is necessary, to ensure smooth performance. The pre-testing period, however, must also include log data collection for checking correctness and quality. User-related aspects such as training and agreements are also necessary. The test plans in general are a joint product of both the test site teams and the evaluation experts. In general, the AWARD evaluation activities are divided into five main areas:

1. User and stakeholder evaluation
2. Safety impact assessment
3. Process efficiency and quality evaluation
4. Environmental impact assessment
5. Technical evaluation.

This paper focuses on measuring efficiency of automated road freight transport, which refers to area 3: Process efficiency and quality evaluation in the AWARD project. For this area, a generic evaluation design is presented in the next section. This generic evaluation design may be tailored to the application in different use cases.

3.2 AWARD Efficiency Evaluation Design

In the AWARD project the object of investigation is an Automated ground Goods Transport System (AGTS). The defined objective of the AGTS is described as "*Automated ground transport of goods in a defined area under harsh weather conditions*". The AGTS comprises different sub-systems such as

- Automated Driving Vehicle (ADV): i.e., the vehicle and its components (interfaces, communications, sensors, etc.). The ADV is in charge of the physical process of moving goods.
- Logistics Operation & Fleet Management (LOFM): This system controls the overall workflow.
- Supporting Infrastructure (SI): This system comprises the physical and digital elements that belong to the infrastructure and will interact with the ADV, e.g., barriers, stationary sensors, etc.
- Supporting Logistics System (SLS): This system is involved in loading/unloading operations.

In the AWARD project, real-world logistics use cases form the basis for demonstrating and evaluating the AGTS. The use cases support summarizing vehicle tasks in different settings, e.g., driving in operational areas or on public roadways, automation of different vehicles such as baggage tractors, trucks, or forklifts. Four generic use cases are studied within the AWARD project: (i) Loading/Unloading and transport with an automated forklift, (ii) Automated baggage tractor operation at the airside of airports, (iii) Hub to hub shuttle service, e.g., from production site to logistics hub, and (iv) Container transfer operations and boat loading at ports. (Fröhlich et al., 2021)

In an initial step, the project partners identified three generic evaluation areas related to efficiency, i.e., fleet efficiency, vehicle efficiency, and the efficiency of handling of goods. As shown in Figure 2, for each area research questions related to the influence on (1) financial indicators, (2) operational indicators, and (3) quality indicates were defined. In the following, hypotheses related to the research questions were formulated and prioritized. Overall, the evaluation experts defined more than 40 hypotheses. Subsequently, Table 3 sketches highly ranked hypotheses related to the research questions for fleet efficiency and vehicle efficiency. In the AWARD project, the research design for the efficiency of handling of goods has also been detailed. However, due to the limited length of the paper, this aspect is not further detailed.

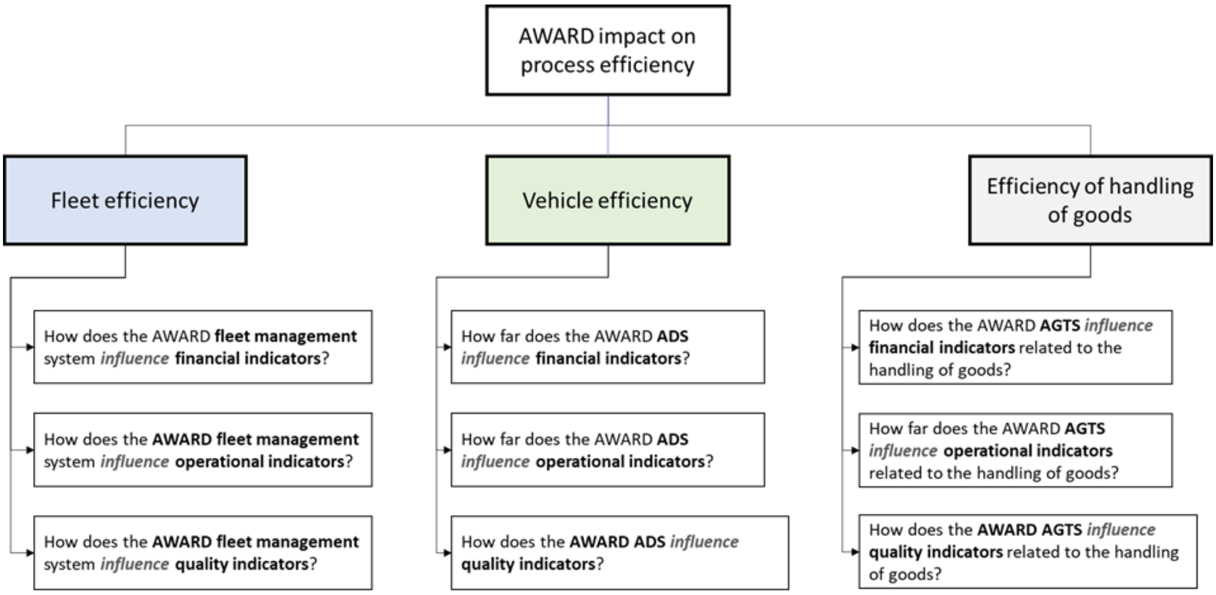

Figure 2: AWARD process efficiency evaluation areas and research questions

Table 3: Research questions and hypotheses related to fleet efficiency and vehicle efficiency

Research Question	Hypothesis
How does the AWARD fleet management system influence financial indicators?	The FMS reduces fuel costs The FMS reduces total costs per kilometer
How does the AWARD fleet management system influence operational indicators?	The FMS increases vehicle utilization The FMS minimizes the distance driven
How does the AWARD fleet management system influence quality indicators?	The FMS minimizes the number of vehicle breakdowns The FMS minimizes the average maintenance downtime
How does the AWARD ADS influence financial indicators?	The ADS supports reducing personnel costs The ADS decreases costs of vehicle operation
How does the AWARD ADS influence operational indicators?	The ADS reduces net transfer time The ADS increases vehicle uptime The ADS decreases personnel time to support (AD) vehicle while driving The ADS reduces fuel consumption The ADS decreases vehicle speed

	The operational availability of the ADS (with respect to varying environmental conditions) is lower than the availability of a manually operated vehicle
How does the AWARD ADS influence quality indicators in operations?	The ADS increases the timeliness of transport orders The ADS increases the transport reliability

The related work presented in this paper supported categorizing the research questions and hypotheses as well as defining measures and data needs to answer them. To investigate the hypotheses and research questions defined in AWARD, a mixed method and data gathering approach will be taken. For each data need, data within the baseline situation of the use case as well as within the AWARD AGTS application situation needs to be collected. However, the data collection will be tailored to the different AWARD use cases depending on the accessibility of data as well as the possibility to collect data during the project duration.

4 Initial Results

The airport use case in AWARD addresses the automated baggage transport at the airside of the Oslo airport in Norway. At the test site, first tests of different transport routes have already been performed with the vehicle and with related safety validation. The tests are performed with a TLD baggage tractor, which is instrumented with EasyMile's level 4 automated driving system and also integrated with the fleet management system (FMS) of Applied Autonomy. This setup allows to dispatch transport orders, record performance measures and any issues while performing the transport task. During the tests, trained operators from Oslo airport accompany the vehicle and additionally report issues in a logbook. The operators report additional information to certain types of stops and reasons they observed. As such automatically collected data from the vehicle and the fleet management system as well as the manually collected data by the operators provide a basis for the efficiency evaluation in the AWARD project. To validate the results also focus groups with vehicle operators are performed.

The targeted long-term advantages of automating baggage tractors identified by the use case stakeholders are (i) reduction in number of drivers / solve driver shortage, (ii) safety improvements, (iii) better utilization of luggage tractor capacity (supported by the FMS), (iv) less driving, if automated vehicle trips are better planned and managed (supported by the FMS), (v) less manual planning with improved fleet management.

The targeted speed of the automated baggage tractor is designed to be similar to human-driven tractors at the airside, with a maximum speed of up to 20 km/h. At present, the vehicle operates at a top speed of 15 km/h in automated mode. Since some other vehicles on-site travel at 30 km/h, the automated tractor is frequently overtaken. Initially, based on focus group discussions, other drivers did seem to get frustrated. However, the situation improved substantially within just a few days, as people became aware that the new vehicle was automated.

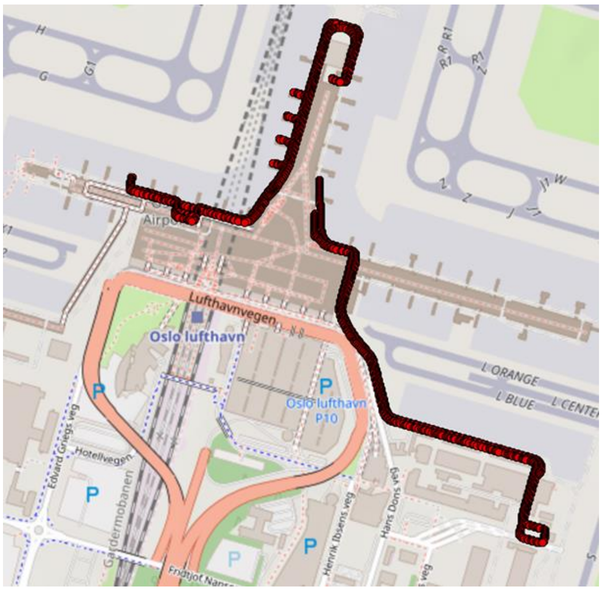

Figure 3: First test routes at Oslo airport. Map created with GPS Visualizer.

The initial tests were conducted during the first half of June 2022, totaling 50 hours of driving. The results indicated efficiency differences between the two different transport routes tested (Figure 3). According to the operators' statements, route 1 was more complex, with more crossings and other surrounding traffic participants. Consequently, the automated tractor required around 50% more time for the route compared to a manually driven tractor. In contrast, for route 2, operators reported only minor differences compared to manually driven tractors. In general, operators felt safe in the vehicle, and no critical situations were observed during the tests. Despite being slower than a human-driven vehicle, the automated vehicle was still fast enough to complete its tasks during the plane turnaround time.

No real-life tests under harsh weather conditions have been conducted thus far. Rain or crossing pedestrians did not significantly impact the tests, with only one safety stop due to rain and one case of the safety driver having to rearm the vehicle after stopping for a pedestrian. The most common reasons reported for safety stops, totaling around 50 each, were annotated as "no obstacle" or "route blocked”. Baggage carts left by human drivers frequently blocked the intended vehicle route at turning points. Improved coordination between human and automated operations or maintaining more separation between them could alleviate such situations.

In these initial tests, safety stops required a safety operator (or, eventually, a teleoperator) to actively support or drive the vehicle for approximately 5 minutes per operational hour. It seems feasible for one teleoperator to oversee multiple vehicles. A comprehensive data analysis across different test phases and technological improvements is still necessary. This ongoing work will offer further insights into the efficiency of the automated transport vehicles developed for the AWARD use cases.

Based on real-world findings, the project will also conduct a simplified efficiency simulation of the test site, considering potential changes to the situation and key performance indicators if more automated vehicles were in use.

5 Conclusion

Efficiency of transport logistics is key. However, challenges in commercial transportation, such as the lack of qualified drivers, the number of fatal accidents with trucks, low load factors, time pressure, 24/7 transportation services, or climate laws demand for innovative transport solutions. Autonomous transport vehicles combined with sustainable propulsion systems may be one innovation to support logistics providers in the near future. In the AWARD project, an automated ground transport system targeted towards harsh weather conditions is developed and tested within four different use cases. To be able to support potential users of automated transport vehicles to take informed decisions with respect to current automation solutions, efficiency evaluation is relevant.

This paper presented the AWARD testing and evaluation methodology. Thereby, specifically the evaluation design regarding process efficiency and quality was presented. Furthermore, related work in the field of measuring transport efficiency informed deriving categories and efficiency measures encoded in the evaluation design. Finally, initial results from one of the AWARD use cases – the airport use case – were sketched. The main evaluation and data gathering activities will be performed in 2023. For this reason, detailed results on concrete efficiency gains or losses with respect to automation are not reported in this paper and present future work.

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