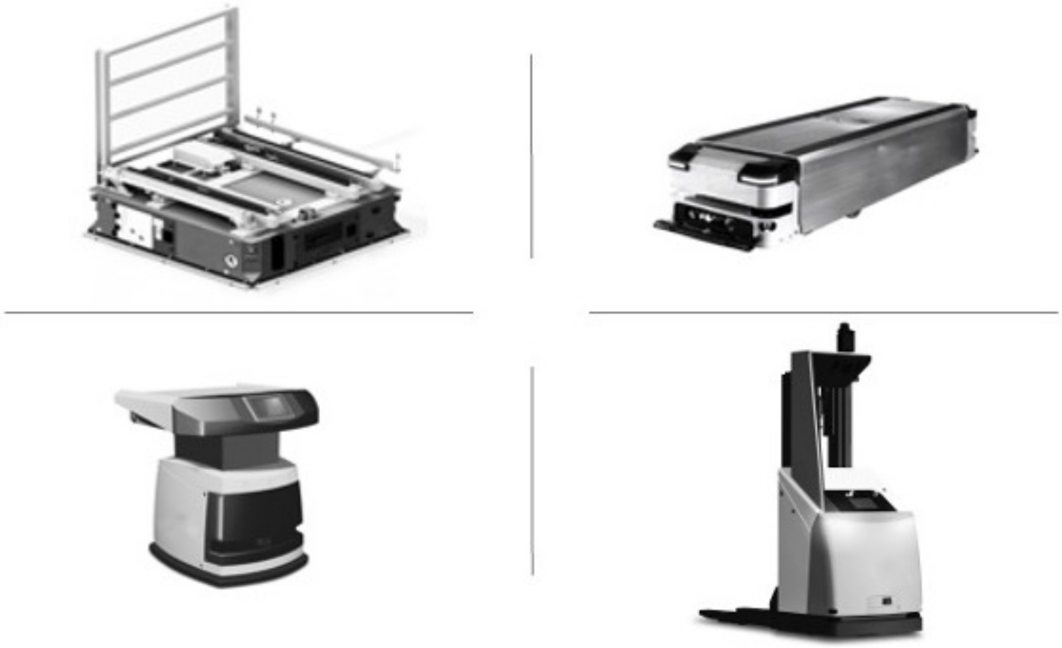
Guide
Autonomy for Mobile Robots

Terms, Definitions, Distinctions, and Introduction to an “Autonomy Index” for driverless transport systems, comprising AGV and AMR



Publisher:

Forum-FTS (www.forum-fts.com)
VDI Technical Committee 309 “Mobile Robotics”

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Issue: June 2026, Version 2.0

This document was prepared by VDI FA 309 “Mobile Robotics” and has been submitted to the VDI technical editorial team for the preparation of a VDI status report.
This document will be withdrawn upon publication of the VDI status report.

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1 Motivation

Whereas in the past there were only AGV and AGV systems, for some time now there have also been AMR, MR, aAGV, IGVs, and other terms that have largely emerged from marketing. In particular, the use of terms such as “autonomy” and “autonomous” is intended to attribute greater value and user benefits to new products with new functions. Since there is no generally accepted understanding – let alone a definition – of the terms “automated,” “fully automated,” “autonomous,” “highly autonomous,” and “intelligent” in the field of intralogistics, this has led to a multitude of offerings that are difficult to compare with one another, resulting in misunderstandings and unmet expectations among users.

The goal of this guide is to establish a common understanding of this terminology and, based on that, to provide a tool for suppliers and users that enables a neutral and practical assessment of the autonomy of driverless transport systems – including AGV and AMR – used in intralogistics.

2 Terminology of Autonomy

The term ***Automated Guided Vehicle System*** (AGV System) has been in use for more than sixty years and describes a logistics system in which a specific logistics task – such as transport to connect sources and sinks, assembly lines for mass-produced goods, or tasks in warehousing and order picking – is carried out by a fleet of automated guided vehicles.

Such an AGV system serves as an organizational tool and ensures reliable, safe material transport with maximum performance, availability, and quality. The peripheral equipment and all logistics and production processes taking place in the surrounding environment are carefully coordinated.

Typical applications include: thoroughly planned, complex logistics processes in companies that engage in series or mass production and require the highest levels of performance and availability in warehousing and order picking.

Typical examples include: automotive manufacturing, automotive supplier companies, logistics centers, mass producers of white and brown goods, the food industry, and the flow of goods in hospitals (food, medication, laundry, waste, etc., outside of patient wards).

The vehicles used in such systems are usually referred to as ***"Automated Guided*** **Vehicles**" (AGV; also "driverless industrial trucks") and can vary greatly in terms of their technological capabilities – both in terms of their functionalities (mechanical, mechatronic, electrical) and their "intelligence" (control functions, sensor technology, autonomy).

For several years now, there have been efforts to shift the focus to the vehicles themselves – and to procure only them (as a product business) – rather than following the traditional AGV approach, which involves procurement as part of a system contract and implementation as a project. These vehicles are often referred to not as AGVs, but as ***mobile robots*** (MR), autonomous mobile robots (AMR), or simply "robots." In addition, there are numerous other terms, many of which are also product names used by individual manufacturers.

The focus is thus on the mobile robot, which can be "easily" integrated into an existing industrial environment and, after a short commissioning period, perform simple tasks (such as transport, handling, cleaning, and providing information). It is possible for a small number of such robots to communicate with one another and share tasks. These vehicles are versatile, require little planning, minimal preparation of the operating environment, and a short commissioning time. They can operate without a stationary AGV control system (fleet manager) if they are able to identify, distribute, and execute their tasks in coordination with the other MRs.

Note: In English-speaking countries, the term "robot" is often not understood in the same way as the German term "Roboter," but rather refers to an automatically operating machine, often an automatically moving mobile platform or an automated vehicle; a robotic arm or manipulator may or may not be present. Similarly, a "robot car" does not refer to a car with a robot mounted on it, but very often simply to a mobile, self-driving platform without any additional attachments or components. Accordingly, "robots" are not necessarily used in industrial environments but can also be found outside of factory buildings and even in public spaces.

Since the MRs and/or AGVs used in such driverless transport systems do not fundamentally differ – though in both cases, functionality, complexity, and intelligence can vary greatly – the VDI guideline series 2510 and 2710, among others, apply equally to both. The guidelines on AGV safety and the AGV safety manuals (for planners and operators) are also applicable and must be followed.

In non-technical contexts, ***autonomy*** refers to a state of self-determination, independence, self-governance, or freedom of decision-making and action. In idealist philosophy, it is the ability to conceive of oneself as a being of freedom and to act out of that freedom. Directly applying the term to the world of technology is obviously difficult and therefore leaves much room for interpretation.

Among the general public, the term "autonomy" in a technical context first gained attention around 2010 in connection with ***autonomous passenger cars*** (self-driving cars on public roads). In technical circles, the *DARPA Grand Challenge* – a competition organized by the U.S. Department of Defense to advance the development of autonomous land vehicles – had already attracted significant attention earlier (in 2004, 2005, and 2007).

Upon closer inspection, the term "autonomous passenger car" is a linguistic inaccuracy, because the relevant standard, SAE J3016[1] – which also forms the basis for the law on automated driving (on approved sections of public roads) passed by the German Bundestag in May 2021 – does not recognize or even mention the term "autonomous." Instead, it describes five different levels of automation. The highest level, in which a driver no longer needs to intervene and is also unable to do so (due to the absence of controls such as a steering wheel, gas/brake pedals, etc.), is referred to as "Full Automation." This Level 5 is often (especially in colloquial speech) also referred to as autonomous driving in German-speaking countries.

If one were to make the absence of a human driver the sole criterion for determining whether a vehicle can or may be described as autonomous, one might conclude that driverless transport vehicles and mobile robots operate autonomously, since, by definition, they are operated without human drivers. Upon closer inspection, however, it becomes clear that human intervention is indeed still possible and necessary in certain situations, meaning that an AGV or mobile robot cannot always react completely independently to all situations that arise during daily operations.

The capabilities of a fully autonomous passenger car thus far exceed the requirements for an AGV or MR in some situations – for example, when driving at high speeds in heavy traffic, in poor visibility (at night, in fog, or in sleet), or when approaching a temporary road closure due to construction. In other areas – for example, positioning tolerances in the range of a few millimeters that must be maintained during load-changing operations – the requirements for AGVs and MRs are, by contrast, significantly higher.

The blanket statement that every AGV or MR is an autonomous vehicle is incorrect, can give the wrong impression, and leads to false assumptions – and yet this is precisely what has been happening with increasing frequency in the recent past. On many manufacturers' websites, the term "autonomous" is used as a synonym for self-driving, driverless, and fully automatic.

To foster an understanding of the breadth of this subject area and to lay the groundwork for the discussions in the following chapters, we first present several statements and explanations regarding the autonomy of technical systems from researchers at leading research institutions.

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[1] Published by SAE International in 2014; original English title: *"Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles"*

Prof. Hans-Jörg Kreowski, Professor (ret.) of Theoretical Computer Science, University of Bremen
Excerpt from a written draft of a lecture on “Autonomy in Technical Systems,” delivered as part of an event hosted by the Leibniz Society of Sciences in Berlin on December 10, 2015; published in March 2018

> “… Autonomy in technical systems today is always human-made, and that is not likely to change anytime soon. It is therefore not autonomy in the philosophical or biological sense, but rather a matter of artifacts – an analogy – just as artificial intelligence is not comparable to human intelligence, and machine learning has little to nothing to do with the learning of living beings. Autonomous technical systems have no consciousness, are not endowed with reason, and cannot think.
>
> The “child” needs a name. In technical and scientific fields, people often use familiar terms when their actual meaning bears certain similarities to the newly named concept. Speaking of technical, artificial, or machine autonomy is therefore entirely understandable, but it must not be confused with the original concept of autonomy. If this distinction is ignored or even deliberately obscured, it is misleading. Unfortunately, this happens frequently in the context of technical autonomy – partly inadvertently, partly intentionally. …”

Human-Machine Interaction: A Handbook on History, Culture, and Ethics,

Editors: Kevin Liggieri, Oliver Müller, Springer-Verlag 2019

Chapter 34 “Automation” by Martina Heßler, TU Darmstadt

> “The term ‘automation’ refers to the delegation of tasks to machines capable of performing them independently. The fundamental goal of automation is to allow a process to run without human intervention. At the core of the concept is the automatic control and regulation of processes based on a feedback control system. […] Automation has consistently changed and shifted the relationship between humans and machines, though not always in the expected way. Attempts at automation have also made it clear what machines cannot (yet) do, thereby underscoring all the more clearly the importance and necessity of human abilities.”

Chapter 35 “Autonomy” by Niels Gottschalk-Mazouz (†), University of Bayreuth

> “Within the context of technical autonomy, degrees of autonomy are typically distinguished as degrees of independence from humans and the environment in the technical execution of specific tasks. […]
> As autonomy increases, the frequency and duration of user interventions typically decrease, and the nature of user interaction changes; it becomes more global, more abstract, and of a higher order. […] Autonomy then refers to the dependence of future behavior solely on the system’s internal states (including sensors), as well as the ability to perform the same task in different situations and different tasks in the same situations. In other words, this concerns internal control, adaptivity, and flexibility. […]
> Third, autonomy is associated with the ability to surprise us. Autonomous systems can therefore learn; they exhibit behaviors not explicitly specified during their design or states and laws unknown to us. In other words, it is about learning, innovation, and unpredictability.”

Blog: Autonomous or perhaps just highly automated—what's the difference, anyway?

Dr. Rasmus Adler, Program Manager "Autonomous Systems," Fraunhofer IESE, Kaiserslautern

(Source: https://www.iese.fraunhofer.de/blog/autonom-oder-vielleicht-doch-nur-hochautomatisiert-was-ist-eigentlich-der-unterschied/)

> "… Both 'autonomous' and 'fully automated' refer to something happening in a goal-oriented manner without human instruction. Recently – especially when it comes to 'automated driving' – these terms are often used interchangeably. …
> If everything has been carefully thought through in advance – no matter how complicated it may be – and we program the well-considered causal relationships into the system, then we refer to it as 'automated.' However, if we do not fully grasp the causal relationships and use AI approaches to only indirectly tell the system how it should behave in a specific situation, then we refer to it as 'autonomous.' …"

German Research Center for Artificial Intelligence – DFKI

(Source: https://www.dfki.de/web/forschung/forschungsthemen/autonome-systeme/)

> "Autonomous systems act independently, learn, solve complex tasks, and can respond to unpredictable events. These are not only traditional robots but also intelligent machines, devices, or software systems that are used in specific areas for the benefit of humans. For example, the mobility of the future will be shaped by autonomous vehicles. Autonomous systems will also support people with disabilities in the home environment. Furthermore, they will be able to interact flexibly with workers in production settings and act autonomously in situations where it is too dangerous for humans. Artificial intelligence provides the key technologies in the areas of machine learning, cybersecurity, and agile IT infrastructures, which are crucial for the further development and deployment of autonomous systems."

Katharina Giese, Fraunhofer IOSB-INA Autonomous Plant Components

(Source: https://www.vdi.de/news/detail/autonome-systeme-wie-und-warum-sollte-man-sie-vergleichen)

> "If we generalize the basic structures of autonomous systems, the following elements emerge …
>
> - **Goal recognition:** Technical systems are designed for specific applications. The first common feature is the goal that such a system helps to achieve.
> - **Independent environmental perception:** Autonomous systems must perceive their environment or context in order to assess the degree to which the objective is being met. This environmental perception is handled, for example, by sensors.
> - **Autonomously Generated Action Plan:** To achieve a given objective, a system must be able to influence its environment in a manner that serves the fulfillment of that objective. An action plan autonomously generated by the system itself forms the transparent basis for its actions.
> - **Resilience and Failsafe Strategies:** These action plans are generated based on historical and current data using, among other things, machine learning and artificial intelligence methods. Resilience is particularly important for achieving independence, as it is the only way the system can respond appropriately to unforeseen events and error conditions. The strategies encompass not only the potential problems anticipated by the developer but also the ability to respond to unexpected events and failures within the system, as well as to develop and implement appropriate failsafe strategies to continue processing the actual task effectively.

3 Distinction Between Automatic and Autonomous Functions

In the following, we do not assume an either/or scenario – AGV or AMR – but rather consider the autonomous functions of a system comprising automated vehicles. We are therefore referring to vehicles that are more or less autonomous, or vehicles with more or fewer autonomous functions. Here, we limit ourselves to functions related to driving, safety, and load handling. It is irrelevant whether these functions are implemented as software locally in the vehicle, in an external cloud, or through a suitable combination of both.

Based on the discussion in the previous chapter, autonomous functions are presented and described in detail below. For the sake of distinction and clarity, however, we will first list functions that, in our view, represent "merely" automatic functions. In our assessment, they do not meet the aforementioned requirements for autonomous operation. This is because autonomous functions are complex. As a rule, they involve situational responses to changing environmental/contextual conditions and system states, which are captured and evaluated using multidimensional sensor data. Proven methods for this include artificial intelligence techniques, such as "machine learning." However, it is also conceivable that comparable results could be achieved through complex high-level language programming.

3.1 AUTOMATIC FUNCTIONS

The most common automatic functions are listed below; this list is not exhaustive.

- **Rail-Guided Driving and Path Guidance**

  Although it may seem trivial, it should be noted that a rail-guided vehicle is neither an AGV (as this contradicts the definition of an AGV) nor can it operate autonomously; therefore, it cannot be an AMR either: Due to the forced guidance provided by the rail(s), degrees of freedom of movement are lacking, since such a vehicle has no further movement options beyond the states specified by the sequence control – "traveling along the rails" (possibly at varying speeds) and "not traveling" (= stopping at selected or externally specified positions). The operating environment is so simple that all events and the resulting states can be "anticipated" by the programmer and programmed into simple if-then decision trees.

- **Traveling on or track guidance via a continuously present, physical track**

  Like guidance via a mechanical rail, guidance using a continuously present physical track – such as an inductive guide wire in the ground, an optical guide line, or magnetic tape on the ground – allows the vehicle no freedom whatsoever regarding its movement; that is, driving off the predetermined guide track is not possible. Thus, while vehicles with this type of lane guidance can automatically transport goods from A to B, they do not perform any movements that a programmer has not previously defined.

- **Position Tracking and Navigation for Virtual Guidance**

  Determining the pose (position and orientation) of a vehicle in space either using additional devices such as floor markings, magnets, reflectors, radio beacons, or other artificial landmarks installed for the system's operation or by utilizing existing environmental features (columns, walls, gates, shelves, machines…). Vehicles using this technology follow a virtual path, which allows for greater flexibility in route planning and route changes.

- **Automatic energy management, i.e., without manual intervention**

  Typically, this involves automatically swapping or recharging the onboard energy storage system at a swap or charging station in conjunction with storage technologies (e.g., batteries, power caps, refillable tanks).

- **Automatic Load Handling**

  Autonomous loading and unloading of loads/load carriers by the vehicle at precisely defined positions and according to precisely specified procedures. This may also include functions such as stacking and unstacking pallets/load carriers.

- **Guided mapping of the operating environment during commissioning and in the event of expansions or modifications**

  Collection of map data for contour-based navigation in previously unknown environments. This is typically done manually using a vehicle or a suitable mobile measurement device (3D scanner, camera(s)) and is usually performed by qualified personnel.

  A map is automatically generated from the collected data. Manual post-processing of this map is usually required. This automatic mapping is performed exclusively during initial commissioning, when expanding the operational area, or when making extensive changes to the operational area.

- **Situation-Based Dynamic Allocation of Transport Orders**

  Situation-dependent, dynamic assignment of transport orders to the entire vehicle fleet, taking into account the current system status (e.g., vehicle position, vehicle availability, vehicle condition, battery charge level, order priority, traffic conditions, etc.).

- **Situation-Based Route Replanning (Dynamic Routing)**

  Dynamic route planning for the entire AGV/AMR fleet, taking into account current traffic and route conditions – for example, actively responding to traffic disruptions caused by the fleet itself.

- **Situational Traffic Control**

  Situational, dynamic traffic control of the AGV/AMR fleet, taking into account the current traffic and facility conditions (e.g., traffic volume, route utilization, order priorities, vehicle positions, vehicle load statuses, battery charge levels, etc.).

- **Self-Diagnosis for Preventive Maintenance**

  Vehicles perform self-diagnostics for preventive maintenance with the goal of reporting wear or the risk of failure in advance so that maintenance can be carried out in a timely and situation-specific manner. This helps prevent unplanned downtime.

- **Responding to Special Operating Conditions**

  Operating conditions are switched by external electrical signals or internally predefined events. Examples include:

  - Response to a fire alarm, typically by clearing escape and rescue routes as well as fire doors
  - Detection of operational interruptions (end of shift, weekends, holidays, company holidays) and switching to an energy-saving sleep mode
  - Detection of the start of operations (after the end of a shift, after the weekend, after holidays, after company holidays) and switching back to normal mode
  - Detection of a failure in a non-travel-related function (e.g., a defect in a load-sensing device) triggers an automatic movement to the service/maintenance area.

3.2 Currently Known AUTONOMOUS Features

The most common autonomous functions are listed below; this list is not exhaustive. Each function is followed by a critical analysis.

The following general statements apply to all functions:

- Generally positive: Autonomous functions promise added value.
- Generally negative: Every additional function entails increased costs due to hardware and/or software and negatively impacts cost-effectiveness.
- General safety aspect: Vehicles with autonomous functions are also subject to the Machinery Directive[2] ! Therefore, a risk assessment in accordance with DIN EN ISO 12100 is always required. Guidance on risk minimization can be found in particular in the relevant Type B standards or the Type C standard DIN EN ISO 3691-4. In the event of deviations, equivalent risk minimization must be demonstrated.
- The operator's risk assessment is equally affected; here, all autonomous functions and their consequences must also be considered. This can make the risk assessment significantly more complex.
- The so-called TOP principle for protective measures must be observed as early as the planning stage. This principle establishes a mandatory hierarchy for occupational safety measures (§4 BetrSichV, §4 ArbSchG) that effectively minimizes hazards. The hierarchy is as follows: 1. Technical (directly at the source), 2. Organizational (work processes), 3. Personal (PPE as a last resort). Measures must be evaluated in this order!

Autonomous functions are not equally suitable or practical for all use cases. Each autonomous function has both positive and negative characteristics, as well as specific safety considerations.

In general, for each autonomous function, it must be determined where (vehicle control system, traffic control system, or fleet manager) decision-making takes place. As a rule, vehicles should inform the control center – if one exists – of their autonomous actions. The more autonomously vehicles behave, the more difficult it becomes for the control center to make predictions about system behavior and system performance.

Autonomous functions require high computing power and, in addition, a high-performance communication system suitable for the task.

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[2] The so-called Machinery Directive (MRL) – more precisely, EU Directive 2006/42/EC – will be replaced as of January 20, 2027, by EU Regulation 2023/1230 – the "Machinery Regulation" (MVO)

1. **Obstacle Avoidance**

Independently avoiding static and dynamic obstacles with the goal of driving around them.

Obstacles are detected at least in two dimensions using appropriate sensors; the vehicle navigates around them using autonomous path planning without predetermined lanes or evasion bays. In this context, 2D environmental sensing covers only the distances between the vehicle and other vehicles, as well as the vehicle's distance from its surroundings, at the sensor level.

To increase operational safety, 3D environmental sensing by the vehicle is recommended. The 3D environmental sensing covers the vehicle's contour, including the load being transported. Navigation is performed while considering the vehicle's contour, including the load, as well as information about other vehicles or objects that may interfere with the currently intended route. This information can be provided by the fleet management system (based on data of stationary sensors) or by other vehicles.

In general, factors such as potential no-passing zones, intersections, junctions, speed limits, vehicle types, etc., should be considered. To this end, it is necessary to deactivate the autonomous "obstacle avoidance" function (in certain sections of the route).

Obstacle avoidance must be coordinated with other road users and, if necessary, reported to the traffic control system.

Obstacle Avoidance with 2D Environmental Sensing

Positive: Disruptions in the workflow caused by temporary obstacles are avoided.

Negative: This function negates the general advantage of an AGV System as a tool for optimizing production logistics processes: The need for cleanliness and order (tidy working environment) diminishes, and processes become more chaotic.
The predictability of vehicle movements decreases which can lead to confusion among employees.
The risk of deadlocks may increase.

Safety: The area used for obstacle avoidance must be clear over the entire height of the vehicle, including its load. The vehicle must maintain the required safety distances in accordance with the Type B standard DIN EN ISO 13854 or a Type C standard such as DIN EN ISO 3691-4.

If the opposite lane is used when maneuvering around an obstacle, the sum of the braking distances of the vehicles involved must be considered for the effective range of the personal safety & protection systems of all vehicles (particularly in heterogeneous fleets with vehicles traveling at different speeds). The safety level is determined by the risk assessment, which must consider the specific characteristics of moving obstacles in the roadway. Personal injury and property damage that may result from collisions between vehicles with significantly different speeds and/or weights must be considered.

The operator is responsible for formulating organizational measures to protect employees and ensuring compliance with them. Depending on the vehicles' sensor equipment, these measures may be very extensive.

Navigating Around Obstacles with 3D Environmental Sensing

Positive: Disruptions to operations caused by temporary obstacles are avoided.

The positive aspects should be greatly enhanced by 3D environmental sensing and the more intelligent behavior it enables.

Negative: This feature negates the general advantage of the AGV as an organizational tool for optimizing production logistics processes; that is, the need for cleanliness and order (a tidy working environment) diminishes.

The predictability of vehicle movements decreases which can lead to confusion among employees in the vicinity of the vehicle. No further disadvantages should arise if implemented properly.

Safety: Same as for 2D environmental sensing. Since the vehicles' sensor equipment is more extensive here than in the previous point, fewer organizational measures are likely to be required.

2. Autonomous, dynamic updating of the operational environment model during operation

An existing map is continuously updated by comparing map data with sensor readings from the vehicles. The goal is to identify new distinctive environmental features, incorporate them into the map, and use them for navigation. Furthermore, environmental features that no longer exist are removed from the map and are no longer used for navigation.

Note:

The updated map data can be exchanged between vehicles directly or indirectly via a third-party system to utilize all vehicles in all areas for dynamic updates while simultaneously keeping all map data on all vehicles up to date. This connectivity supports and enhances the autonomous functions described in this chapter.

Positive: Constantly up-to-date map data enables robust localization with fewer disruptions. Since no temporary objects captured during initial mapping need to be deleted through manual post-processing, commissioning and maintenance efforts are reduced.

Negative: Since measurement errors accumulate (e.g., with a small number of static features such as columns and walls), there is a risk that inaccuracies will arise in the map. Localization performance deteriorates, and the stability of the processes suffers.

Safety: The expected inaccuracies are in the low double-digit centimeter range and accumulate over a longer period of time; they do not occur suddenly. For this reason, this function does not raise any specific safety concerns. In the event of larger inaccuracies leading to significant deviations from the original lane, the vehicle's safety systems would activate in a timely manner.

3. Driving on Approved Areas

In addition to physical or virtual lanes, designated areas can also be used. Within these areas, the vehicle can independently plan and follow its route, generally while adhering to rules such as keeping to the right, maintaining minimum lateral distances from fixed structures, other vehicles, people, etc.

Positive: This feature reduces the effort required for commissioning, particularly for heterogeneous vehicle fleets, since (distance) rules are automatically adhered to. It also reduces the ongoing effort required when changes are made to the designated areas and/or the arrangement of layout elements (e.g., sources, sinks, loading areas, etc.).

Negative: To take advantage of the system's flexibility, larger areas should be kept clear. This increases the space requirement compared to planned fixed lanes.
Care should also be taken when allocating open areas, as the entire cleared area must be free over the full height of the vehicle, including its load. The probability of collisions with objects unknown at the time of commissioning (e.g., stepladders, fork tips, drawbars, suspended loads, etc.) is greater in cleared areas than on predetermined lanes.
The predictability of vehicle movements decreases, which can lead to confusion among

employees.
The throughput of the entire system fluctuates and is difficult to predict.

Safety: The cleared areas must be free of obstacles over the entire height of the vehicle, including the load. To ensure compliance with safety distances, measures meeting the required safety level – at a minimum in accordance with the Type B standard DIN EN ISO 13854 – must be implemented.

4. Navigation and Response Based on Object Detection and Classification

Detection and classification of objects (e.g., pallets, people, industrial trucks, motor vehicles) and, where applicable, their direction of movement, as well as an appropriate response derived from this information. This generally requires 3D environmental sensing. The sensors required for this are either mounted on the vehicle or are available externally, either stationary or mobile.

Typical behavior: Navigating around static obstacles, reacting to and avoiding moving people, and yielding the right of way to vehicles approaching from the right.

Positive: The vehicle adapts to its environment and responds appropriately. It can also handle more challenging environments. Disruptions caused by temporary obstacles are avoided, and process stability increases. Safety-critical situations can be better detected, assessed, and, if necessary, avoided through proactive action.

Negative: Due to the more complex technology, system costs are higher. If object detection or classification is faulty, the risk of inappropriate behavior increases.

When it comes to obstacle avoidance, the same disadvantages apply as in item 1.

Safety: The safety requirements correspond to those specified in Item 1. Risk assessment becomes significantly more complex.

5. Load handling based on object detection and classification

Autonomous approach, pickup, and delivery of loads/load carriers by the vehicle at roughly defined positions, including adjustment to the exact load position based on object detection and classification.

This may also include functions such as automatically adjusting the load-handling equipment to the classified load (e.g., adjusting the fork tines to fit the detected load carrier). Classifying the load in terms of its transportability (load weight, load dimensions/protrusions, load securing if applicable, quality of the loading equipment, etc.) and the load-dependent selection of personal protection zones requires a sensor solution and/or communication system specifically designed for this purpose. The sensor technology required for this can be either stationary or mobile.

For safety-related functions, this solution must achieve the required performance level in accordance with the Machinery Directive / Machinery Regulation. Here, too, the sensor technology used can be mounted on the vehicle or located externally.

Advantage: This function forms the basis for greater process reliability and more flexibility in load handling, thereby significantly simplifying the load positioning process. With manual loading (e.g., using a pallet jack, forklift, or similar equipment), the load unit no longer needs to be positioned as precisely. With automatic loading (e.g., roller or chain conveyors) of different load units – which may vary in width – centering devices can be eliminated.

Classifying the load may enable automatic adjustment of the load-handling equipment and, additionally, the generation of transport order destinations.

Drawback: Vehicles may require more space and more time to maneuver around inaccurately positioned load units.

Safety: Safety-related requirements become more stringent.

The vehicle must maintain the required safety distances when approaching load-handling positions. If it falls short of the safety distances, additional measures must be implemented to ensure the appropriate safety level.

Caution: Depending on the situation, safety fields may need to be switched based on the classification of different load units with the corresponding safety level.

6. Situational route replanning in mixed-traffic operations

Dynamic route replanning for the entire AGV/AMR fleet in mixed-traffic operations, i.e., taking into account other industrial trucks and road users. This includes consideration of current traffic conditions and/or system utilization, as well as actively responding to traffic disruptions caused by the fleet itself, other road users, or other objects.

This requires that the automatic function “Situational Route Replanning (Dynamic Routing)” be available.

Note: The effectiveness of this function depends on the quality of the data, particularly the location information regarding other road users / objects, as well as the expected duration of the traffic disruption.

If this information is exchanged at the vehicle level, a high-performance communication system is required.

Positive: An obstruction caused by other road users does not disrupt the flow of traffic. By rerouting, the destination may still be reached if necessary.

Negative: The additional time required for the alternative route may be greater than the extended travel time on the original route caused by the obstruction.

It is no longer possible to plan transport orders precisely in terms of the execution time per order, and processes aimed at ensuring exact, demand-driven delivery are made more difficult.

There is a risk that employees will overuse the feature, for example, by making obstacles on the route the norm and/or failing to remove them promptly.

Safety: No additional measures are required as long as the road network consists solely of suitable routes.

7. Autonomous Response to Traffic Situations in Mixed Traffic

Vehicle behavior that considers not only its own AGV/AMR fleet but also mixed traffic consisting of industrial trucks and other road users.

It requires the system to independently recognize signs (traffic signs, traffic lights) and situations (people, groups of people, obstacles, traffic volume, construction zones, road narrowings, etc.). This enables an appropriate response tailored to the situation.

Note: The effectiveness of this function depends on the quality of the data, particularly the location information regarding other road users and the detection of objects.

Positive: It allows for flexible responses to complex traffic situations, which may result in higher throughput for the overall system.

Negative: Extensive sensor technology and software for environmental sensing and classification are required to achieve good results. This entails high implementation costs.

Safety: Critical situations may be mitigated, but new critical situations may also arise. Risk and hazard assessments become significantly more complex.

8. **Autonomous detection and response to vehicle condition data without disrupting ongoing operations**

Vehicles analyze condition data (e.g., sluggish drivetrains, significantly increased slip, insufficiently accurate localization, power supply issues, …) and respond to unforeseen conditions based on the situation. For example, they attempt to autonomously remove themselves from the flow of traffic and from the system – if necessary, at reduced speed – so as not to pose an obstacle to the rest of the fleet. This may involve, for example, proceeding to locations defined in the layout, such as maintenance bays, passing bays, parking spaces, etc. Depending on the system design, the journey to these locations may be conducted autonomously or with support from the fleet management system.

Regardless of whether the vehicle can remove itself from traffic or not, it should send a message to the fleet management system.

Positive: This results in fewer obstructions and blockages for the remaining vehicles.

Negative: This function requires sophisticated, sensor-based data processing within the vehicle, which may entail higher costs.

Safety: No specific safety requirements apply to this function. The requirements described above apply to any subsequent driving.

9. **Partial or complete transfer of control functions to the vehicle side**

This refers to a fleet of two or more vehicles in which decision-making tasks are delegated to the vehicles, thereby eliminating the need for central control functions.

Examples of such decision-making tasks include the distribution of transport orders to individual vehicles (complete elimination of a central control system) or the regulation of traffic in specific traffic areas such as intersections and junctions or at transfer stations (without involving the traffic management system). Multi-agent systems or decentralized negotiation strategies may be used for this purpose. A mandatory prerequisite for such decentralized decision-making tasks is a comprehensive, high-performance (broadband, fast, low-latency), and highly available wireless communication system.

Another example is the joint execution of special tasks, such as the transport of loads that, due to their weight and/or dimensions, cannot be handled by a single vehicle. In this case, two or more autonomously operating vehicles independently and jointly – physically by coupling or virtually through software-based synchronization – form a corresponding convoy capable of handling the transport of the load. Once the task is complete, the convoy disbands on its own.

The autonomous grouping of vehicles into a convoy without a central control system constitutes an autonomy function, whereas the joint execution of the transport is considered an automatic function.

Advantage: Distributing the functions across multiple computers results in greater resilience and system availability.

Drawback: Each vehicle requires a high-performance computer, and a high-performance radio communication system is needed within the vehicles' operational area. Both of these factors may lead to higher costs.

Safety: It must be determined whether the combination of multiple vehicles creates what is known as a "safety-related system." If this is the case, CE certification is required not only for the individual vehicles but also for the vehicle network (see VDI Technical Status Report – AGV Safety Guidelines for Planners).

10. Planning and Execution of Complex Sequences of Actions

This refers to a mobile robot's ability, either alone or in a group and without prior explicit and time-consuming programming, to perform complex tasks – e.g., "load the truck at Dock 3 with the pallets from staging zone 5," "unload the truck at Dock 4 and place the pallets in staging zone 2," "sort the pallets in staging zone 7 into four status classes and transport them to zones 1 through 4," "clean the floor in Terminal 2, arrival level" – to carry out these tasks autonomously. This presupposes the presence of (almost) all nine autonomy functions described above, and also requires the ability to independently break down the assigned task into a logical sequence of work steps to be carried out one after another (which are currently typically specified by a central control system).

This tenth, somewhat visionary autonomy function is deliberately listed last, as it requires a maximum level of capabilities – and thus sensors, signal processing, and software functionality – and vehicles with this functionality are not yet in practical use (as of April 2026). However, they already exist in the laboratories of research and development institutions and are thus on the threshold of practical application.

Positive: This function allows the operator to use the vehicles flexibly, with the ability to switch between different tasks and application areas, without requiring support (programming) from the vehicle manufacturer.

Negative: Each vehicle requires extensive sensor equipment, a powerful computer, and sophisticated software (most likely AI-based). This leads to higher costs.

Safety: The requirements described above apply to this function.

4 Calculation of Autonomy and Requirement Compliance Index

Now that the previous chapter has described both typical automated functions and a range of currently possible or common autonomous functions of mobile robots, an Excel worksheet will be used to determine

- which autonomy functions are present in the system under consideration (whether already in use or planned/in the procurement phase)
- and to what extent each function is relevant (meaningful, useful, necessary) for the specific use case.

The result is thus

- the **Autonomy Index (AIx)**: a classification of the vehicle or vehicle system in terms of its autonomy, and
- the **Requirement Fulfilment Index (AEIx)**: an assessment of the solution in terms of its relevance to a specific task.

The AIx is calculated as the sum of the available autonomy functions, based on all ten functions described in Section 3.2.

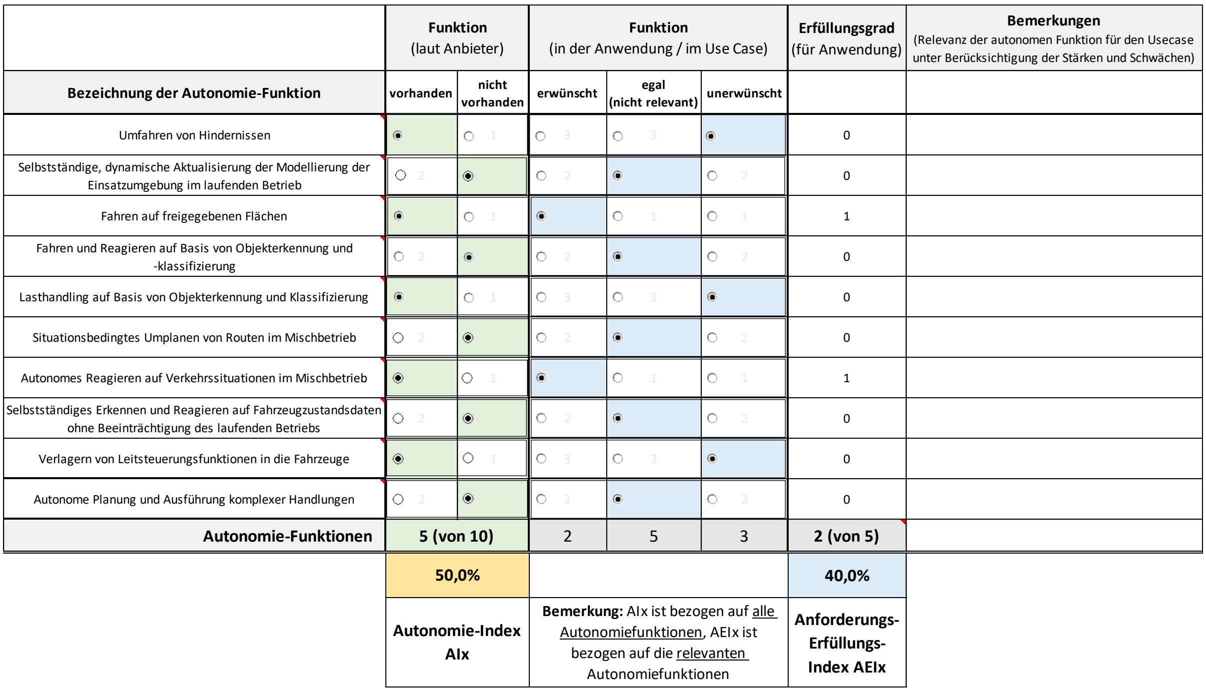
The AEIx is derived from comparing the AIx with the application's requirements. In doing so, the user must evaluate all autonomy functions in terms of their necessity for the application in question: desired – irrelevant – undesired.

An autonomous function isn't inherently good or bad –
rather, it must be suited to the specific application!

For example, "autonomous obstacle avoidance" is certainly a productivity-enhancing and therefore necessary function for a cleaning robot in an airport terminal – however, for an AGV in a production environment designed for precise timing and maximum throughput of the transport system, it may not be the most effective solution.

The functionality of the method and the use of the spreadsheet will be illustrated using two practical examples from the AGV/AMR supplier DS Automotion (Linz, Austria). The first example describes an in-house application: an assembly line for electric vehicle batteries. The second example is an application in publicly accessible areas: courier deliveries in a hospital. These completely different use cases clearly illustrate how varied the requirements and the solutions employed can be.

Screenshot of the Excel tool “vdi-fa-fts-amr-autonomie_April2026-V2.xlsx”[3]



	Funktion (laut Anbieter)		**Funktion** (in der Anwendung / im Use Case)			**Erfüllungsgrad** (für Anwendung)	**Bemerkungen** (Relevanz der autonomen Funktion für den Usecase unter Berücksichtigung der Stärken und Schwächen)
Bezeichnung der Autonomie-Funktion	**vorhanden**	**nicht vorhanden**	**erwünscht**	**egal (nicht relevant)**	**unerwünscht**		
Umfahren von Hindernissen	●	○ 1	○ 3	○ 3	●	0	
Selbstständige, dynamische Aktualisierung der Modellierung der Einsatzumgebung im laufenden Betrieb	○ 2	●	○ 2	●	○ 2	0	
Fahren auf freigegebenen Flächen	●	○ 1	●	○ 1	○ 1	1	
Fahren und Reagieren auf Basis von Objekterkennung und -klassifizierung	○ 2	●	○ 2	●	○ 2	0	
Lasthandling auf Basis von Objekterkennung und Klassifizierung	●	○ 1	○ 3	○ 3	●	0	
Situationsbedingtes Umplanen von Routen im Mischbetrieb	○ 2	●	○ 2	●	○ 2	0	
Autonomes Reagieren auf Verkehrssituationen im Mischbetrieb	●	○ 1	●	○ 1	○ 1	1	
Selbstständiges Erkennen und Reagieren auf Fahrzeugzustandsdaten ohne Beeinträchtigung des laufenden Betriebs	○ 2	●	○ 2	●	○ 2	0	
Verlagern von Leitsteuerungsfunktionen in die Fahrzeuge	●	○ 1	○ 3	○ 3	●	0	
Autonome Planung und Ausführung komplexer Handlungen	○ 2	●	○ 2	●	○ 2	0	
Autonomie-Funktionen	**5 (von 10)**		2	5	3	**2 (von 5)**	
	50,0%					**40,0%**	
	Autonomie-Index AIx		**Bemerkung:** AIx ist bezogen auf alle Autonomiefunktionen, AEIx ist bezogen auf die relevanten Autonomiefunktionen			**Anforderungs-Erfüllungs-Index AEIx**	

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[3] The Excel tool has the filename “vdi-fts-amr-autonomie_April-2026_v2.xlsx.” The file is available for free use; the rights belong to the VDI Technical Committee FA 309; unauthorized modifications are not permitted.

4.1 Example 1: AGVs in Battery Assembly

Deutsche Akkumotive in Kamenz produces batteries (high-voltage storage units) for electric cars. The assembly line is equipped with automated guided vehicles (AGVs) on which the high-voltage batteries are transported and assembled. A fleet of 50 AGVs handles logistics processes in a “taxi” mode across the various areas of the entire plant. Another fleet of approximately 100 vehicles of the same type supports the assembly processes in a “shuttle” mode (Fig. 1.6).

Table 1.1 shows how the relatively low autonomy index of 30% for the AGVs aligns with the application: The requirement fulfilment index is over 83%. The notes provide additional case-specific details for each autonomy function. This section also explains why certain autonomy functions are undesirable in this application.

Table 1.1 Autonomy Index and Requirement Fulfilment Index for the Assembly AGV

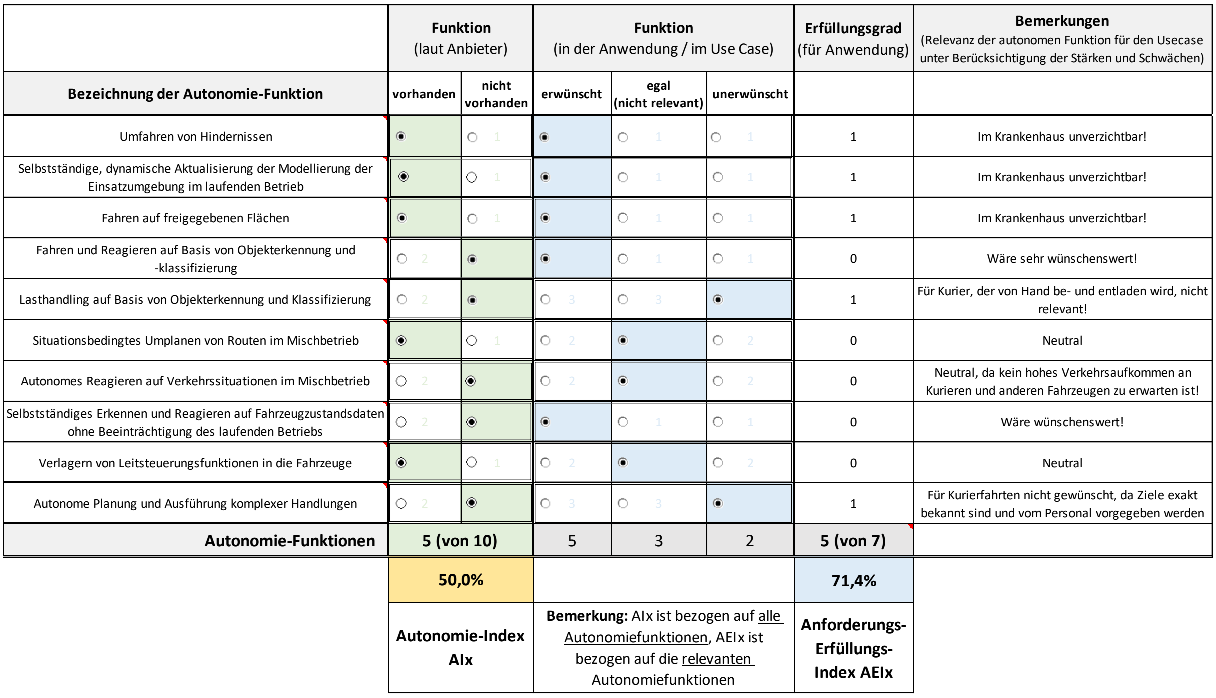
		Funktion (laut Anbieter)		**Funktion** (in der Anwendung / im Use Case)			**Erfüllungsgrad** (für Anwendung)	**Bemerkungen** (Relevanz der autonomen Funktion für den Usecase unter Berücksichtigung der Stärken und Schwächen)
Pos.	**Bezeichnung der Autonomie-Funktion**	**vorhanden**	**nicht vorhanden**	**erwünscht**	**egal (nicht relevant)**	**unerwünscht**		
1	Umfahren von Hindernissen	○ 2	●	○ 3	○ 3	●	1	Im Montageumfeld kritisch!
2	Selbstständige, dynamische Aktualisierung der Modellierung der Einsatzumgebung im laufenden Betrieb	●	○ 1	●	○ 1	○ 1	1	Für stabile Navigation wichtig!
3	Fahren auf freigegebenen Flächen	○ 2	●	○ 3	○ 3	●	1	Im Montageumfeld kritisch!
4	Fahren und Reagieren auf Basis von Objekterkennung und -klassifizierung	○ 2	●	○ 2	●	○ 2	0	Wäre wünschenswert, FTF kann aber auf Grund vorgegebener Fahrwege nur bedingt reagieren!
5	Lasthandling auf Basis von Objekterkennung und Klassifizierung	○ 2	●	○ 2	●	○ 2	0	Last ist klar definiert, somit kein Vorteil!
6	Situationsbedingtes Umplanen von Routen im Mischbetrieb	●	○ 1	●	○ 1	○ 1	1	Sofern Alternativrouten möglich sind, wünschenswert!
7	Autonomes Reagieren auf Verkehrssituationen im Mischbetrieb	○ 2	●	●	○ 1	○ 1	0	Im Montageumfeld durchaus von Vorteil!
8	Selbstständiges Erkennen und Reagieren auf Fahrzeugzustandsdaten ohne Beeinträchtigung des laufenden Betriebs	○ 2	●	○ 2	●	○ 2	0	Wäre wünschenswert, FTF kann aber auf Grund vorgegebener Abläufe nur bedingt reagieren!
9	Verlagern von Leitsteuerungsfunktionen in die Fahrzeuge	●	○ 1	○ 2	●	○ 2	0	Neutral
10	Autonome Planung und Ausführung komplexer Handlungen	○ 2	●	○ 3	○ 3	●	1	Im Montageumfeld nicht sinnvoll, da klare Prozesse vorhanden sind!
	Autonomie-Funktionen	**3 (von 10)**		3	4	3	**5 (von 6)**	
		30,0%					**83,3%**	
		Autonomie-Index AIx		**Bemerkung:** AIx ist bezogen auf alle Autonomiefunktionen, AEIx ist bezogen auf die relevanten Autonomiefunktionen			**Anforderungs-Erfüllungs-Index AEIx**	

4.2 Example 2: AMR for Courier Runs in a Hospital

At the University Hospital of Cologne, mobile robots are used for courier runs between the central pharmacy and various wards. Authorized pharmacy and ward staff load and unload the robots with medications. The route passes through public areas with patients, visitors, and ward staff (Fig. 1.7).

This application requires significantly more autonomy functions than the one in the first example. Table 1.2 shows an autonomy index of 50% for the mobile robots. Comparing this with the requirements of the use case results in a high requirement fulfillment index of over 70%. This clearly demonstrates the robot's suitability for the application (in terms of autonomy)!

Table 1.2 Autonomy Index and Requirement Fulfilment Index for the Courier AMR



	Funktion (laut Anbieter)		**Funktion** (in der Anwendung / im Use Case)			**Erfüllungsgrad** (für Anwendung)	**Bemerkungen** (Relevanz der autonomen Funktion für den Usecase unter Berücksichtigung der Stärken und Schwächen)
Bezeichnung der Autonomie-Funktion	**vorhanden**	**nicht vorhanden**	**erwünscht**	**egal (nicht relevant)**	**unerwünscht**		
Umfahren von Hindernissen	●	○ 1	●	○ 1	○ 1	1	Im Krankenhaus unverzichtbar!
Selbstständige, dynamische Aktualisierung der Modellierung der Einsatzumgebung im laufenden Betrieb	●	○ 1	●	○ 1	○ 1	1	Im Krankenhaus unverzichtbar!
Fahren auf freigegebenen Flächen	●	○ 1	●	○ 1	○ 1	1	Im Krankenhaus unverzichtbar!
Fahren und Reagieren auf Basis von Objekterkennung und -klassifizierung	○ 2	●	●	○ 1	○ 1	0	Wäre sehr wünschenswert!
Lasthandling auf Basis von Objekterkennung und Klassifizierung	○ 2	●	○ 3	○ 3	●	1	Für Kurier, der von Hand be- und entladen wird, nicht relevant!
Situationsbedingtes Umplanen von Routen im Mischbetrieb	●	○ 1	○ 2	●	○ 2	0	Neutral
Autonomes Reagieren auf Verkehrssituationen im Mischbetrieb	○ 2	●	○ 2	●	○ 2	0	Neutral, da kein hohes Verkehrsaufkommen an Kurieren und anderen Fahrzeugen zu erwarten ist!
Selbstständiges Erkennen und Reagieren auf Fahrzeugzustandsdaten ohne Beeinträchtigung des laufenden Betriebs	○ 2	●	●	○ 1	○ 1	0	Wäre wünschenswert!
Verlagern von Leitsteuerungsfunktionen in die Fahrzeuge	●	○ 1	○ 2	●	○ 2	0	Neutral
Autonome Planung und Ausführung komplexer Handlungen	○ 2	●	○ 3	○ 3	●	1	Für Kurierfahrten nicht gewünscht, da Ziele exakt bekannt sind und vom Personal vorgegeben werden
Autonomie-Funktionen	**5 (von 10)**		5	3	2	**5 (von 7)**	
	50,0%					**71,4%**	
	Autonomie-Index AIx		**Bemerkung:** AIx ist bezogen auf alle Autonomiefunktionen, AEIx ist bezogen auf die relevanten Autonomiefunktionen			**Anforderungs-Erfüllungs-Index AEIx**	

This courier robot has five of the ten total autonomy functions, which is a high number. It should be emphasized here that implementing these autonomy functions is technically challenging, and some functions are not yet part of the standard equipment of AMRs. The table shows that functions 4 and 8 would certainly be desirable from the customer's perspective but are not (yet) available as part of the robot's functional scope.

5 Summary and Outlook

The use of the term "autonomy" in connection with mobile robots is not regulated by any law, ordinance, directive, or similar legislation – meaning that any manufacturer may describe its product as autonomous without fear of problems or disadvantages. Even experts who have been studying the subject for years find it difficult to provide a clear, concise definition of the term *autonomy* as it applies to technical systems, and our research ultimately failed to uncover one.

This guide was developed as part of a technical examination of the topic:

- A distinction is made between the terms *"automatic"* and *"autonomous*,"
- presented currently known automation and autonomy functions used in practice,
- evaluated the autonomous functions in terms of their characteristics and benefits for the user, while also highlighting safety aspects, and
- developed an easy-to-use, neutral, practical, and meaningful analysis and evaluation tool.

In terms of these definitions, this means: A driverless transport system (AGV system) consists of a fleet management system and an AGV or a fleet of multiple AGVs and/or AMRs. If an AGV possesses at least one autonomous function of the type described above, it can justifiably be referred to as an AMR (Autonomous Mobile Robot).

This establishes, on the one hand, the basis for an objective discussion of the topic and, on the other hand, enables users to compare offerings from different manufacturers and evaluate their suitability for their current application. The publication should also be understood as a call to industry stakeholders to critically engage with the topic and to bring the use of the term *autonomous* back to an appropriate and technically justified level.

This second version of the guide has been comprehensively revised – particularly in Section 3.2 – adapted to current developments and findings, and, compared to the previous version, better structured and made more clearly organized. Furthermore, two real-world applications of mobile robots are used as examples to demonstrate the use of the EXCEL tool for determining the Autonomy Index and the Autonomy Fulfilment Index, and the results obtained are explained.

Recent years have shown that the topics of autonomy and AI applications in mobile robotics are constantly and rapidly evolving. Therefore, this guide will incorporate future developments as they arise.

6 Abbreviations and Terms

aAGV	autonomous AGV
AGV	Automated Guided Vehicle
AGVS	Automated Guided Vehicle System
AMR	Autonomous Mobile Robot
Throughput	Transport capacity × availability
FF	Forum-FTS (www.forum-fts.com)
FFZ	Material Handling Vehicle
FTF	German abbreviation, equals AGV
FTS	German abbreviation, equals AGV System
IGV	Intelligent Guided Vehicle
MR	Mobile Robot
VDI	www.vdi.de (Association of German Engineers)
VDI FA 309	Technical Committee on “Mobile Robotics” chaired by Dr. Günter Ullrich and Peter Stoiber; from early 1987 through September 2025, the committee was known as “Automated Guided Vehicles (AGVs).”