AGV Guide
Autonomy of Mobile Robots

Terms, explanations, delimitations
and presentation of an
"Autonomy Index" for AGV / AMR

Published by:

Forum-FTS (www.forum-fts.com)

Edition: July 2023, version 1.2
Published by members of the VDI Technical Committee FA 309 "Automated Guided Vehicle Systems"

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This document is available to the technical editors of the VDI to create a VDI status report.
This document will be withdrawn with the publication of the VDI status report.

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1 Motivation

Where there used to be only AGVs and FTFs, today there are also AMRs, MRs, aAGVs, IGVs and other terms that have largely sprung from marketing. In particular, by using the terms autonomy / autonomous, attempts are made to ascribe a higher value and user benefit to new products with new functions. Since there is no generally accepted understanding of the terms automated, fully automated, autonomous, highly autonomous and intelligent in the field of intralogistics, there is a multitude of offers that are difficult to compare with each other and, as a result, misunderstandings and disappointed expectations among users.

The aim of this guide is to achieve a common understanding of this conceptual world and, based on this, to provide suppliers and users with a tool that enables a neutral and practicable evaluation of the autonomy of automated guided vehicles (AGV / AMR) used in intralogistics.

2 Conceptual World of Autonomy

The term "**Automated Guided Vehicle System**" (AGV System) has been used for more than sixty years and describes a logistics system with which a specific logistics task - for example, transports for linking start and target destinations; assembly lines for series products; or a task in warehousing and order picking - is carried out by means of a fleet of automated industrial trucks.

Such an AGV sees itself as an organisational tool and guarantor for reliable, safe materials transport with maximum performance, availability and quality. The periphery and all logistics and production processes in the environment are carefully coordinated.

Typical applications are: well-planned, complex logistics processes in companies that produce by means of series / mass production and require maximum performance and efficiency in warehousing and commissioning.

Typical examples are: Automotive manufacturing, automotive supply companies, logistics centres, serial producers of white and brown goods, food industry, flow of goods in hospitals (food, medicine, laundry, waste etc., away from the wards).

The vehicles used in such systems are usually called ***Automated Guided Vehicles*** (AGVs; also driverless trucks) and can differ greatly technologically in terms of their functionalities (mechanical, mechatronic, electrical) but also in terms of their "intelligence" (sensors, control functions, autonomy).

For some years now, there have been efforts to focus on the vehicles and only procure them (product business), in contrast to the classic AGV, which is procured as part of a system business and realised as a project. These vehicles are often not referred to as AGVs, but as ***mobile robots*** (MR), autonomous mobile robots (AMR), or simply "robots". In addition, there are numerous other designations, which are often also product names of individual manufacturers.

The focus is therefore on mobile robots that can be "easily" integrated into an existing industrial environment and take over simple services (such as transports, handling, cleaning, information) after a short commissioning time. It is possible for a few such robots to communicate with each other and share tasks. Such vehicles can be used in a variety of ways, require little planning, hardly any preparation of the operational environment and short commissioning times. They may be able to function without a stationary AGV master control system if they find, distribute and execute their tasks themselves in coordination with the other MRs.

Note: In the Anglo-Saxon language area, the term "robot" is often not understood in the same way as the German term "Roboter", but rather stands for an automatically operating machine, often also an automatically travelling mobile platform / vehicle; a robot arm / manipulator can but does not have to be present. Thus, a "robot car" does not refer to a car with a robot mounted on it, but very often only to a mobile, automatically travelling platform without any further attachments/components. Accordingly, "robots" are not necessarily used in industrial environments but can also be found outside of workshops and even in public spaces.

Since the MRs and / or AGVs used in such AGV Systems do not differ fundamentally - but in both cases functionality, complexity and intelligence can vary greatly - the VDI guideline series 2510 and 2710, among others, apply equally to both. The standards on AGV safety and the AGV safety guidelines (for planners and users) are also applicable and must be used.

In non-technical fields, ***autonomy*** refers to a state of self-determination, independence, self-government or freedom of decision or action. In idealistic philosophy, it is the ability to conceive of oneself as a being of freedom and to act out of this freedom. A direct transferability of the term to the world of technology is obviously difficult and therefore offers much room for interpretation.

The general public first became aware of the term autonomy in a technical context around 2010 in connection with ***autonomous cars*** (self-driving cars on public roads). In technically interested circles, the *DARPA Grand Challenge*, which was set up as a competition by the US Department of Defense to advance the development of autonomously driving land vehicles, had already attracted a great deal of attention (2004, 2005, 2007).

On closer inspection, the term "autonomous car" is a linguistic inaccuracy, because the relevant standard SAE J3016[1] , which also forms the basis for the law on automatic driving (on approved sections of public roads) recently passed by the German Bundestag, does not know or mention the term "autonomous" at all. Much more five different levels of automation are described. The highest level, in which the driver does not need to and cannot intervene (due to the lack of operating elements such as steering wheel, accelerator/brake pedal, etc.), is called "full automation". This level 5 is often referred to (especially colloquially) in German-speaking countries as autonomous driving.

If one now makes the absence of a human driver the - sole - criterion for deciding whether a vehicle can/should be described as autonomous, one could conclude that automated guided vehicles and mobile robots act autonomously because they are operated without a human driver by definition. However, a closer look reveals that human intervention is still possible and necessary in certain situations, i.e. that an AGV/MR cannot always react completely autonomously to all situations that occur during daily operations.

In some situations - e.g. driving at high speeds and with heavy traffic, in poor visibility (at night, in fog or sleet), when approaching a temporary lane closure due to a construction site - the capabilities of a fully automated car go far beyond the requirements of an AGV/MR. In other areas - for example, positioning tolerances in the range of a few millimetres to be maintained during load change operations - the requirements for AGVs/MRs are much higher.

The blanket statement that every AGV/MR is an autonomous vehicle is incorrect, can create a false impression and leads to false assumptions - and yet this is precisely what has been happening more and more frequently in the recent past. On many manufacturers' websites, the term "autonomous" is used as a synonym for self-driving, driverless and fully automated.

In order to gain an understanding of the breadth of the subject area and to form the basis for the explanations in the following chapters, a few statements and explanations on the autonomy of technical systems by employees of authoritative research institutions follow first.

Prof. Hans-Jörg Kreowski, Professor (retired) of Theoretical Computer Science, University of Bremen

[1] 2014 published by SAE International, original title "*Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles".*

Excerpt from a written elaboration of a lecture on "Autonomy in technical systems" given at an event of the Leibniz-Sozietät der Wissenschaften zu Berlin on 10 December 2015; published in March 2018 (Originally published in German, translated by DeepL.com)

"... Autonomy in technical systems today is always man-made and this will not change for the time being. So we are not talking about autonomy in the sense of philosophy and biology, but about artefacts, an analogy, similar to how artificial intelligence is not comparable to human intelligence and machine learning has little or nothing to do with the learning of living beings. Autonomous technical systems have no consciousness, are not capable of reason, cannot think.

The "child" needs a name. In the technical-scientific field, one likes to use familiar terms if their actual meaning has certain similarities with the new name. To speak of technical, artificial, machine autonomy is thus quite understandable, but must not be confused with the original concept of autonomy. If this difference is not taken into account or even deliberately covered up, this is misleading. Unfortunately, this often happens in connection with technical autonomy - sometimes carelessly, sometimes deliberately. ..."

Human-Machine Interaction, Handbook on History - Culture - Ethics,

Editors: Kevin Liggieri, Oliver Müller, Springer-Verlag 2019
(Originally published in German, translated by DeepL.com)

Chapter 34 "Automation / Automation" by Martina Heßler, TU Darmstadt

"The term "automation" refers to the delegation of activities to machines that are in a position to carry them out independently. The basic goal of automate is to run a process without human action. The core of the term is the automatic control and monitoring of processes on the basis of a feedback control system. [...] Automate has always changed and shifted the ratio between humans and machines, but not always in the expected way. Thus, attempts at automation also made clear what machines cannot (yet) do and underlined all the more clearly the importance and necessity of human skills."

Ch. 35 "Autonomy" by Niels Gottschalk-Mazouz(†), University of Bayreuth

"Within technical autonomy, degrees of autonomy are usually distinguished as degrees of independence from humans and the environment in the technical execution of certain tasks. [...]
As autonomy increases, the frequency and duration of user interventions typically decreases and the nature of user interaction changes; it becomes more global, abstract and high-level. [...]
Autonomy then refers to the dependence of future behaviour only on internal states of the system (including sensors), as well as the capabilities to perform the same job in different situations and different jobs in the same situations. In other words, this is about inner control, adaptivity and flexibility. [...]
Thirdly, autonomy is associated with the ability to surprise us. Autonomous systems can therefore learn, do not have explicitly predetermined behaviours or unknown states and laws in their design. In other words, it is about learning, innovation and unpredictability."

Blog: Autonomous or perhaps just highly automated, what is actually the difference?

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/)

(Originally published in German, translated by DeepL.com)

"... Both autonomous and fully automated refer to something happening purposefully and without human instruction. Recently, the terms have often been used synonymously - especially when it comes to the topic of "automated driving". ...
If everything has been thought out in advance, no matter how complicated it is, and we program the system with the thought-out causal relationships, then we are talking about automated. But if we don't really grasp the causal relationships at all and only indirectly tell the system with AI approaches how it should behave in a certain situation, then we talk about autonomous. ..."

German Centre for Artificial Intelligence - DFKI

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

(Originally published in German, translated by DeepL.com)

"Autonomous systems act independently, learn, solve complex tasks and can react to unpredictable events. These are not only classic robots, but also intelligent machines, devices or software systems that are used in the interest of humans in special areas. For example, the mobility of the future will be determined by autonomous vehicles. Autonomous systems will also support impaired people in the domestic environment. In addition, they will be able to interact flexibly with workers in production and act autonomously where it is too dangerous for humans. Artificial intelligence provides the key technologies in machine learning, cyber security and agile IT infrastructures that are essential 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)

(Originally published in German, translated by DeepL.com)

"If one generalises the basic structures of autonomous systems, the elements result ...

- **Goal recognition:** Technical systems are designed for specific application purposes. The first common feature is the goal that such a system helps to fulfil.
- **Autonomous environment detection:** Autonomous systems must perceive their environment or context in order to be able to assess the degree of goal fulfilment. Sensors, for example, take on this task of sensing the environment.
- **Self-generated plan of action:** To achieve a given goal, a system must be able to influence the environment in a way that is conducive to goal fulfilment. A plan of action generated autonomously by the autonomous system forms the comprehensible basis of the actions.

- **Resilience and failsafe strategies:** These action plans are generated on the basis of historical and current data using machine learning and artificial intelligence methods, among others. Resilience is particularly important for achieving independence. Because only in this way can the system react appropriately to unforeseen events and error states. The strategies do not only include the potential problems preconceived by the developer. They also include the ability to react to unexpected events as well as failures within the system, to develop and implement appropriate failsafe strategies in order to continue processing the actual task appropriately.

..."

3 Differentiation Between Automatic And Autonomous Functions

In the following, we do not assume an either/or - AGV or AMR - but consider autonomous functions of a system with automatic vehicles. We are therefore talking about vehicles with more or less autonomous functions. Here we restrict ourselves to functions for driving, safety and load handling. It is irrelevant whether the functions are realised as software locally in the vehicle, in a central master control system, in an external cloud or a suitable combination.

Based on the explanations in the previous chapter, autonomous functions are presented and described in detail below. For the sake of delimitation and clarification, however, we will first explain functions which, according to our understanding, are "only" automatic functions. In our opinion, they do not meet the aforementioned requirements for autonomous action. This is because autonomous functions are complex. As a rule, they involve situational reactions to changing environmental/framework conditions and system states, which are recorded and evaluated by means of multi-dimensional sensor information. Probate means for this are artificial intelligence methods, e.g. "machine learning". However, it is also conceivable that comparable results can be achieved in complex high-level language programming.

3.1 AUTOMATIC Functions

- **Driving on or guiding by means of rails**

  Even if it seems trivial, it should be pointed out that a vehicle guided by the rail is neither an FTF (contradicts the definition of an FTF) nor can it act autonomously, i.e. it cannot be an AMR either: due to the forced guidance by the rail, there is no degree of freedom of movement, since such a vehicle has no further movement possibilities apart from the states "driving along the rail" - possibly at different speeds - and "not driving" (= stop at selected or externally specified positions), which are predefined by the sequence control. The operational environment is so less complex that all events and the states derived from them can be "thought out" by the programmer and programmed in a simple "if-then-decision" tree.

- **Driving on or guiding by means of a continuously available physical guiding line**

  Similar to guiding by a mechanical rail, guiding by means of a continuously existing physical guiding line - inductive guiding wire in the ground, optical line or magnetic tape on the ground - does not allow the vehicle any freedom with regard to its movement, i.e. driving off the predefined guiding line is not possible. Thus, vehicles with this type of guiding can automatically transport goods from A to B, but they do not perform any movement that a programmer has not previously specified.

- **Localisation and navigation for virtual lane guidance**

  Determining the pose (position and orientation) of a vehicle in space either with additional devices such as floor labelling, magnets, reflectors, radio anchors or other artificial landmarks attached/mounted for the operation of the system or by means of already existing environmental features (pillars, walls, gates, racks, machines...). Vehicles using this technology follow a virtual lane, allowing greater flexibility in driving course design and changes.

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

  Typically, the automatic changing or recharging of the onboard energy storage device at a changing or charging station in conjunction with storage technologies (e.g. batteries, power caps, tanks for refilling).

- **Automatic load handling**

  Independent pick-up and delivery of loads/load carriers by the vehicle at precisely defined positions and according to precisely defined procedures. This can also include functions such as stacking and destacking pallets/load carriers.

- **Guided mapping of the operational environment during commissioning and extensions/changes**

  Recording of map data for contour-based navigation in previously unknown surroundings. This is typically done manually with a vehicle or with a mobile measuring device suitable for this purpose (3D scanner, camera(s)) and is usually carried out by specialised personnel.

  A map is automatically created with the recorded data. As a rule, manual post-processing of this map is necessary. This automatic mapping is carried out exclusively within the scope of an initial commissioning, within the scope of the extension of the application or within the scope of a more extensive change of the application.

- **Situation-dependent dynamic distribution of transport orders**

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

- **Situation-based rescheduling of routes by the system (dynamic routing)**

  Dynamic route planning for the entire AGV/AMR fleet, taking into account current traffic conditions and/or system utilisation, as well as active reaction to traffic disruptions by the own fleet.

- **Situation-based traffic regulation**

  Situation-based, dynamic traffic control of the AGV/AMR fleet, taking into account the current traffic and facility situation (e.g. traffic volume, traffic conditions, order priority, vehicle position, vehicle loading status/battery charge status, etc.).

- **Self diagnosis for preventive maintenance**

  Vehicles carry out a self diagnosis for preventive maintenance with the aim of reporting wear and tear or the risk of failure in advance so that maintenance can be carried out in good time and depending on the situation. In this way, premature failure can be avoided.

- **Responding to special operation states**

  Operation states are switched by external electrical signals or internally fixed parameterised events. Examples of this are:

  - Reaction to fire alarms, usually the clearing of escape and rescue routes as well as fire doors.
  - Detection of operational interruptions (end of shift, weekend, public holidays, company holiday) and switching off into an energy-saving snooze mode
  - Detection of start of operation (after end of shift, after weekend, after public holidays, after company holiday) and switching back to normal mode
  - Detection of the failure of a non-driving relevant function (e.g. defect of a load suspension device sensor) leads to automatic travelling to the service/maintenance area.

3.2 Currently known AUTONOMOUS functions

1. Independent, dynamic updating of the modelling of the operational environment during operation

Continuous recording of map data by the vehicles in conjunction with dynamic updating of the mapping of the operational environment.

The aim is to identify new prominent environmental features and to include them in the mapping and use them for navigation. Furthermore, environmental features that are no longer present are removed from the mapping and no longer used for navigation.

Ideally, the updated map data will be shared between vehicles in order to use all vehicles in all areas for dynamic updating, while keeping all map data on all vehicles up to date.

2. Driving on released areas without predefined physical or virtual guiding lines

In addition to physical or virtual guiding, optional travelling on cleared areas.

On these areas, the vehicle can plan and follow its route independently, usually taking into account rules such as the right-hand drive, keeping a minimum distance from fixed installations, other vehicles, people, etc.

3. Driving around obstacles

Independent avoidance of static and dynamic obstacles with the aim of driving around them.

The obstacles are detected at least two-dimensionally with suitable sensors, and the bypass is carried out with independent route planning without predefined traffic lanes or avoidance bays.

4. Situational avoidance of obstacles with 3D environment detection

Independent avoidance of static and dynamic obstacles with the aim of driving around them.

The 3D environment detection covers the contour of the vehicle including the load to be transported. The bypass is carried out considering the contour of the vehicle including the load as well as information about other vehicles or objects that may be in the way of the currently intended bypass. This information can be provided by the master control system or directly by other vehicles. The route planning is carried out by the vehicle independently and without predefined traffic lanes or avoidance bays.

5. **Acting based on object recognition and classification**

   Detection of different objects (e.g. pallets, people, forklift trucks, motor vehicles) and, if present, their direction of movement, as well as the associated adapted reaction to them.

   Typical behaviour: Avoiding static obstacles, reacting to moving people and taking evasive action, e.g. giving way to vehicles coming from the right, but not pure load handling. This usually requires a 3D environment detection. The sensors required for this are either located on the vehicle or are mounted stationary (covering the entire area).

6. **Load handling based on object recognition and classification**

   Independent approach, pick-up and delivery of load / load carriers by the vehicle at roughly defined positions, including adjustment to the exact load position based on the recognition of the objects and their classification.

   This can also include functions such as the independent adjustment of the Load pickup to the classified load (adjust forks to recognised load carrier). The classification of the load with regard to its transportability (load weight, load dimensions/ overhangs, load securing if necessary, quality of the loading aid, etc.) and the load-dependent selection of the personal protection fields requires a sensor solution especially suited for this purpose.

   For safety-relevant functions, this solution must achieve the required performance level according to the machinery directive. Here, too, the sensors can be mounted either on the vehicle or stationary.

7. **Situational rescheduling of routes in mixed operations**

   Dynamic route planning for the entire AGV/AMR fleet, taking into account other industrial trucks and road users. The current traffic conditions and/or system utilisation are taken into account, as well as the active reaction to traffic disruptions caused by the own fleet, other road users or other objects.

   Here it is assumed that the automatic function "Situational rescheduling of routes by the system (Dynamic Routing)" is available.

   Note: The effectiveness of the function depends on the quality of the data, especially the localisation information.

8. **Traffic regulation taking into account mixed operation**

   Traffic regulation based on rules (general, temporary or spatially limited) or signs (traffic signs, traffic lights) that takes into account not only the company's own AGV/AMR fleet but also mixed traffic consisting of industrial trucks and other road users.

   Here it is assumed that the automatic function "Situation-based traffic control" is available.

9. **Independent detection and reaction to vehicle condition data without interfering with ongoing operation**

   Vehicles evaluate status data (e.g. sluggish drives, greatly increased slip, insufficiently precise localisation, problems with the energy supply, ...) and react to unforeseen situations dependent. For example, they independently try to take themselves out of the traffic flow and out of the system, at reduced speed if needed, so as not to be an obstacle for the rest of the fleet.

10. **Partial or complete relocation of control functions to the vehicle side**

In the case of a fleet of two or more vehicles, this refers to the outsourcing of decision-making tasks to the vehicles without centralised control functions.

Examples of such decision-making tasks are the distribution of transport orders to individual vehicles (completely under waiver of a master control system) or the regulation of traffic in individual traffic areas such as crossings and junctions or at load transfer stations (without involving the master control system). Multi-agent systems or decentralised negotiation strategies can be used here. An essential prerequisite for such decentralised decision-making tasks is a high-performance (broadband, fast, low-latency) and area-wide radio communication system.

A special case is the joint execution of special tasks, such as the transport of loads, which cannot be carried out by one vehicle alone due to their weight and/or dimensions. In this case, two or more vehicles form a corresponding network physically by coupling or virtually by software synchronisation, which can handle the transport of the load. Once the task is completed, the group dissolves independently.

4 Determination of Autonomy and Fulfilment Index

After describing both typical automatic functions and a number of currently possible or common autonomous functions of automated guided vehicles in the previous chapter, an EXCEL worksheet will now be used to record

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

The result is therefore

- the ***Autonomy Index*** **(AIx)**: a classification of the vehicle or vehicle system in terms of its autonomy; and
- the **R*equirement Fulfilment Index*** **(AEIx**)[2]: an assessment of the solution in terms of its suitability for a specific task.

The AIx is calculated from the sum of the existing, related to all ten autonomy functions described in chapter 3.2.

The AEIx results from the comparison of the AIx with the requirements of the application. In the process, all autonomy functions must be evaluated by the user in terms of their necessity for the application under consideration: desirable - indifferent - not desirable.

An autonomous function is not fundamentally good or bad -
it must rather fit the respective application!

For example, the "autonomous obstacle avoidance" for the cleaning robot in the airport hall is certainly a function that increases productivity and is therefore necessary - but for an AGV in a synchronised production designed for the greatest possible efficiency of the transport system, it may not be purposeful.

[2] "AEIx" refers to German translation

Excel tool with macros: "FF-fts-amr-autonomy-macro_Dez-2021_v100.xlsm"

		Function (according to supplier)		Function (with regard to the use case)			Fulfillment rate (for the use case)	Comment (Relevance of the autonomous function with regard to the use case, taking into account its strengths and weaknesses)
no.	**Description of the AUTONOMOUS functions**	**available**	**not available**	**desired**	**it doesn't matter (not relevant)**	**not desired**		
1	Dynamic updating of the modelling of the operational environment	◉	○ 1	◉	○ 1	○ 1	1	
2	Driving on released areas	○ 2	◉	○ 2	◉	○ 2	0	
3	Driving around obstacles	◉	○ 1	○ 3	○ 3	◉	0	
4	Situational avoidance of obstacles with 3D environment detection	○ 2	◉	○ 2	◉	○ 2	0	
5	Acting based on object recognition and classification	◉	○ 1	◉	○ 1	○ 1	1	
6	Load handling based on object recognition and classification	○ 2	◉	○ 2	◉	○ 2	0	
7	Situational rescheduling of routes in mixed operations	◉	○ 1	○ 3	○ 3	◉	0	
8	Traffic regulation taking into account mixed operation	○ 2	◉	○ 2	◉	○ 2	0	
9	Independent detection and reaction to vehicle condition data	◉	○ 1	◉	○ 1	○ 1	1	
10	Relocation of control functions to the vehicle side	○ 2	◉	○ 2	◉	○ 2	0	
	Autonomous functions	**5 (out of 10)**		3	5	2	**3 (out of 5)**	
		50,0%					**60,0%**	
		Autonomy Index AIx		**Comment:** AIx is related to all autonomy functions, AEIx is related to the relevant autonomy functions			**Requirements Fulfillment Index AEIx**	

An autonomous function is not fundamentally good or bad - it must rather fit the respective application!

Excel tool without macros: "FF-fts-amr-autonomy_Dez-2021_v100.xlsx"

		Function (according to supplier)		Function (with regard to the use case)			Fulfillment rate (for the use case)	Comment (Relevance of the autonomous function with regard to the use case, taking into account its strengths and weaknesses)
no.	**Description of the AUTONOMOUS functions**	**available**	**not available**	**desired**	**it doesn't matter (not relevant)**	**not desired**		
1	Dynamic updating of the modelling of the operational environment	x		x			1	
2	Driving on released areas		x		x		0	
3	Driving around obstacles	x				x	0	
4	Situational avoidance of obstacles with 3D environment detection		x		x		0	
5	Acting based on object recognition and classification	x		x			1	
6	Load handling based on object recognition and classification		x		x		0	
7	Situational rescheduling of routes in mixed operations	x				x	0	
8	Traffic regulation taking into account mixed operation		x		x		0	
9	Independent detection and reaction to vehicle condition data	x		x			1	
10	Relocation of control functions to the vehicle side		x		x		0	
	Autonomous functions	**5 (out of 10)**		3	5	2	**3 (out of 5)**	
		50,0%					**60,0%**	
		Autonomy Index AIx		**Comment:** AIx is related to all autonomy functions, AEIx is related to the relevant autonomy functions			**Requirements Fulfillment Index AEIx**	

5 Critical Discussion on The Autonomy Functions

The following general statements apply to all functions:

- Generally positive: autonomous functions promise added value.
- Generally negative: Every additional function means increased costs due to hardware and/or software and burdens profitability.
- General safety aspect: Vehicles with autonomous functions are also subject to the machinery directive! A risk assessment in accordance with DIN EN ISO 12100 is therefore always required. Information on risk minimisation can be found in particular in the corresponding type B standards or the type C standard DIN EN ISO 3691-4. In the event of deviations, equivalent risk minimisation must be demonstrated.

However, the autonomy functions are not equally suitable or useful for all use cases (applications). Each autonomy function has positive and negative characteristics as well as special safety aspects. These will be pointed out in the following.

1. **Independent, dynamic updating of the modelling of the operational environment in running operation**

   Continuous recording of map data by the vehicles in conjunction with dynamic updating of the mapping of the operational environment.

   The aim is to identify new prominent environmental features and to include them in the mapping and use them for navigation. Furthermore, environmental features that are no longer present are removed from the mapping and no longer used for navigation.

   Ideally, the updated map data will be shared between vehicles in order to use all vehicles in all areas for dynamic updating and at the same time keep all map data on all vehicles up to date.

   Positive: By always having up-to-date map data, one achieves a robust localisation and possibly fewer disturbances during localisation.
   Since no temporary objects recorded during initial mapping have to be deleted by manual post-processing, the commissioning and maintenance effort is reduced.

   Negative: There is a risk that inaccuracies creep into the localisation and are only recognised (too) late.

   Safety: The function has no special safety aspects.

2. **Travelling on released areas without predefined physical or virtual tracks**

   In addition to physical or virtual guidance, optional driving on cleared areas. On these areas, the vehicle can plan and drive its route independently, usually taking into account rules such as the right-hand driving rule, keeping minimum lateral distances to fixed installations, other vehicles, people, etc. The vehicle can also drive on the right-hand side of the road.

   Positive: This function ensures less commissioning effort, especially with heterogeneous vehicle fleets, as (distance) rules are automatically observed. Also, the ongoing effort for changes of the released areas and/or the arrangement of layout elements (e.g. starts, target destinations; finishes, loading bays, etc.) is lower.

   Negative: If the released area is used, the floor space required will also be greater - compared to planned fixed lanes.
   Care should also be taken when allocating the free areas, as the entire free area must be free over the entire height of the vehicle including the load. The probability of collisions with

objects that are not known at the time of commissioning (e.g. triangular ladder, fork tip, drawbar, suspended load, etc.) is greater on cleared areas than on predefined tracks.
The predictability of vehicle movements decreases which can lead to irritation among the staff.

Safety: The cleared areas must be free over the complete height of the vehicle incl. load. To maintain the safety margins, measures with the required safety level at least according to type B standard DIN EN ISO 13854 must be implemented.

3. Driving around obstacles

Independent avoidance of static and dynamic obstacles with the aim of driving around them. The obstacles are detected at least two-dimensionally with suitable sensors, the avoidance takes place with independent route planning without predefined traffic lanes or avoidance bays.

Positive: Disruptions in the process due to temporary obstacles are avoided.

Negative: This function cancels out the general advantage of the AGV as an organisational tool to optimise the processes of production logistics: The compulsion for cleanliness and order (tidy operational environment) diminishes and the processes become more chaotic.
The predictability of vehicle movements decreases which can lead to irritation among employees.
The danger of deadlocks increases.

Safety: The area used for obstacle avoidance must be clear over the entire height of the vehicle incl. load. The vehicle must maintain the required safety margins according to the type B standard DIN EN ISO 13854 or a C standard such as DIN EN ISO 3691-4.

If the oncoming lane is used when driving around an obstacle, the sum of the braking distances of the vehicles involved must be taken into account for the range of the person detection devices, if necessary (especially in heterogeneous fleets). The safety level results from the risk assessment. This must take into account personal injuries that may result from the collision.

It is the responsibility of the user to formulate organisational measures for the protection of the employees and to ensure that they are complied with. Depending on the sensors of the vehicles, these measures can be very extensive.

4. Situational avoidance of obstacles with 3D environment detection

Independent avoidance of static and dynamic obstacles with the aim of travelling around them. The 3D environment detection covers the contour of the vehicle including the load to be transported. The avoidance takes place under consideration of the vehicle contour including the load as well as under consideration of information about other vehicles that may be in the way of the currently intended avoidance. This information can be provided by the master control system or directly by other vehicles. The route planning is carried out by the vehicle independently and without predefined traffic lanes or avoidance bays.

Positive: According to no. 3.
The positive aspects should be greatly improved by the 3D environment detection and the more intelligent action that is possible with it.

Negative: This function cancels out the general advantage of the AGV as an organisational tool to optimise the processes of production logistics, i.e. the compulsion for cleanliness and order (to a cleared operational environment) diminishes.

The predictability of vehicle movements decreases which can lead to irritation among employees. Other disadvantages should not occur with good implementation.

Safety: According to No. 3. As the sensors on the vehicles are more extensive here than in the previous point, fewer organisational measures are likely to be required.

5. Acting based on object recognition and classification

Detection of different objects (e.g. pallets, persons, industrial trucks, motor vehicles) and, if present, their direction of movement, as well as the associated adapted reaction to them. Typical behaviour: Avoiding static obstacles, reacting to moving persons and taking evasive action, e.g. giving way to vehicles coming from the right, but not pure load handling. This usually requires a 3D environment detection. The sensors required for this are either located on the vehicle, mounted stationary (covering the entire area) or a combination of these.

This function is a basic autonomous function and can be considered a prerequisite for intelligent behaviour of the AGV/AMR.

Positive: The vehicle can adapt to its environment and react appropriately. It can also cope with more demanding environments.

Negative: If this potential is only used to bypass obstacles, the same disadvantages apply as in No. 3. / 4.

Safety: The safety requirements are as specified in No. 4. with a safety level corresponding to the risk assessment.

6. Load handling based on object recognition and classification

Independent approach, pick-up and delivery of load / load carriers by the vehicle at roughly defined positions, including adjustment to the exact load position based on the recognition of the objects and their classification.

This can also include functions such as the independent adjustment of the load handling device with reference to the classified load (adjust forks to recognised load carrier). The classification of the load with regard to its transportability (load weight, load dimensions/ overhangs, load securing if necessary, quality of the loading aid, etc.) and the load-dependent selection of the personal protection fields requires a sensor solution especially suited for this purpose. For safety-relevant functions, this solution must achieve the required performance level according to the machinery directive. Here, too, the sensors can be mounted either on the vehicle or stationary.

Positive: This function is the basis for more error tolerance in load handling: It simplifies load provisioning considerably. During manual provision (e.g. with pallet truck/forklift truck...), the load unit no longer has to be positioned so precisely. With automatic provision (e.g. roller/chain conveyor...) of different load units, possibly also of different widths, centering devices can be dispensed with.

The susceptibility to faults decreases and the availability increases.

Negative: Vehicles may need more space to maneuver in front of inaccurately provided load units.

Safety: Safety-relevant requirements are becoming more demanding.

The vehicle must maintain the required safety margins when approaching load handling positions. If it falls below the safety margins, additional measures with the corresponding safety level must be implemented.

Attention: If necessary, the switching of protective fields due to different loading units must be implemented with the corresponding safety level.

During planning and commissioning, the focus should be on the technical protective devices (e.g. safety light curtain, fences, anti-standing devices...). Furthermore, organisational protective measures (e.g. floor labelling, signage, staff training...) must be taken.

7. **Situational rescheduling of routes in mixed operations**

Dynamic route planning for the entire AGV/AMR fleet, taking into account other industrial trucks and road users. The current traffic conditions and/or system utilisation are taken into account, as well as the active reaction to traffic disruptions caused by the own fleet, other road users or other objects.

Here it is assumed that the automatic function "Situational rescheduling of routes by the system (Dynamic Routing)" is available.

Note: The effectiveness of the function depends on the quality of the data, especially the localisation information.

Positive: In the event of an obstruction/disruption on the planned route to the destination, transport orders can still be completed.

Negative: The time supplement for the alternative route may take longer than the longer travel time on the original route missed due to the obstruction. There is a risk that the function is misused by employees, e.g. by making obstacles in the driveway the rule and/or not removing them promptly. Precise planning of transport orders in terms of execution time per order is no longer possible. Precisely planned processes with the aim of an exact delivery according to demand are made more difficult.

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

8. **Traffic regulation taking into account mixed operation**

Traffic regulation based on rules (general, temporary or spatially limited) or signs (traffic signs, traffic lights) that takes into account not only the company's own AGV/AMR fleet but also mixed traffic consisting of industrial trucks and other road users.

Here it is assumed that the automatic function "Situation-based traffic control" is available.

Positive: A higher throughput of the entire system can be achieved.

Negative: Extensive sensors and software are needed to capture the environment and classify it in order to achieve a good result. This means a high implementation effort (costs).

Safety: Just as with the automatic function "Situation-based traffic control", the risk assessment must take into account personal injuries that may result from a collision.

9. **Independent detection and reaction to vehicle condition data without interfering with ongoing operation**

Vehicles evaluate status data (e.g. sluggish drives, greatly increased slip, insufficiently accurate localisation, energy supply problems, ...) and react to unforeseen conditions depending on the situation. For example, they independently try to take themselves out of the traffic flow and out of the system, at reduced speed if needed, so as not to be an obstacle for the rest of the fleet.

Positive: A higher throughput can be achieved for the remaining vehicles.

Negative: For this to be possible, additional sensors including intelligent evaluation are required in the vehicle.

Safety: No additional safety requirements are necessary compared to normal operation.

10. Partial or complete relocation of control functions to the vehicle side

In the case of a fleet of two or more vehicles, this refers to the outsourcing of decision-making tasks to the vehicles without centralised control functions. Examples of such decision-making tasks are the distribution of transport orders to individual vehicles (completely under waiver of a master control system) or the regulation of traffic in individual traffic areas such as crossings and junctions or at load transfer stations (without involving the master control system). Multi-agent systems or decentralised negotiation strategies can be used here. A mandatory prerequisite for such decentralised decision-making tasks is a high-performance (broadband, fast, low-latency) and area-wide radio communication system.

A special case is the joint execution of special tasks, such as the transport of loads that cannot be carried out by one vehicle alone due to their weight and/or dimensions. In this case, two or more vehicles form a corresponding network physically by coupling or virtually by software synchronisation, which can handle the transport of the load. After completion of the task, the group dissolves independently.

Positive: By distributing the function to several computers, a higher resilience is achieved.

Negative: Each vehicle needs a correspondingly powerful computer, and a powerful radio communication system is required. Both may lead to higher costs.

Safety: It must be checked whether a safety-related coherence arises from the relocation. If this is the case, CE certification is required not only for the individual vehicles but for the entire system (see VDI Statusreport Technik - FTS-Leitfaden Sicherheit für Planer).
In the case of a vehicle network, there is always a so-called safety-related coherence, irrespective of the relocation of master control functions.

6 Summary And Outlook

The VDI Expert Committee on AGVs publishes this guide in the hope of making it easier to deal with the modern terminology of AGVs/AMRs. The aim is to provide a neutral, practicable and meaningful tool with which offered/described AGV/AMR solutions can be evaluated with regard to autonomy. The attached EXCEL tool[3] fulfils these requirements. It is available in two versions, namely an input-optimised version that uses macros and a simple version without macros.

The authors of this guide are aware that not all readers/users will agree with everything that is said. Even though an attempt has been made here to work in an unbiased, neutral, and competent manner, further discussion is intended. It can therefore be assumed that there will be new, improved versions of the text and the Excel tool at irregular intervals. Contributions to the discussion can be sent by mail to: vdi@forum-fts.com

7 Abbreviations And Terms

AGV	Automated Guided Vehicle
AGVS	Automated Guided Vehicle System
AMR	Autonomous Mobile Robot
Throughput	Transport capacity x Availability
FF	Forum-FTS (www.forum-fts.com)
FTF	German for AGV
FTS	German for AGV System
MR	Mobile Robot
VDI	Association of German Engineers (www.vdi.de)

[3] The two versions of the EXCEL tool have the file names “FF-fts-amr-autonomy_Dez-2021_v100.xlsx” and “FF-fts-amr-autonomy-macro_Dez-2021_v100.xlsm”. The files are available for free use, the rights are held by the VDI Technical Committee FA 309; unauthorised changes are not permitted.