The AGV

Highway Code

Developed in collaboration with

AIRBUS

Contents

Introduction

This Highway Code applies specifically to the use of automated or autonomous guided vehicles (AGV). To keep the information presented as generic as possible no specific case has been used in the development.

This project emerged as a result of two simple questions - what type of rules does an AGV operate by, and what is an AGV capable of? Realising the importance of understanding this from both a safety perspective (when humans work alongside with AGVs) as well as a utility perspective (understanding what type of situation the utility of an AGV can be retrofitted), a rigorous literature review was performed, revealing a large gap in research that mixes the AGV rules, categories and ideas. Thus, the idea of creating a Highway Code, which accumulates all the different rules regardless of their category, was born. Presented in both an Excel toolkit and a paper guide version of the Highway Code, the project resulted in 53 rules/algorithms related to AGVs being identified, four categories for the rules defined, and finally, a user-friendly overview of the different functions related to how an AGV works.

Most of the rules presented in the Code have been collected from secondary sources, such as AGV producers web pages and academic papers. Every source is provided for every presented rule. It should, therefore, be noted that the Code does not attempt to claim 'ownership' of any of the rules presented, nor does it attempt to claim that the presented sources are the rule(s) inventor.

Moreover, although various and rigorous validation methods have been used, the reader should be made aware that because the Highway Code is the first of its kind and, more importantly, as of now the first edition, it may be subject to future changes. Any suggestions for possible improvements or feedback is greatly appreciated.

Construction of the Highway Code

In this section, the construction and methodology used to develop the Highway Code are presented and elaborated upon.

In terms of methodology, the process of constructing the code has been split up into two phases: Phase One and Phase Two. For simplicity, figure 1 has been constructed in the form of a flow chart to illustrate the process.

Phase One

The first phase of the methodology aims at establishing the database. Without the database, the Highway Code cannot be established, making it a natural starting point for the phase. To collect the data, two approaches were used. The first, primary data, which was collected partially through interviews, using a developed questionnaire, with industry employees who work with AGVs, and partially, through information collected via the observation during Gemba walks in the factory where the AGVs operated. Once the primary data had been collected, it was analysed with the intention of identifying categories and means of classification. This was also done for the secondary data, which was collected through screening various academic papers and AGV productions companies' web pages for rules. In total, four major categories were found: Dispatchment, Load-Selection, Routing Method and Traffic Regulation.

Within these categories, classifications were established, to further define the characteristics of an individual rule.

Phase Two

Once the database had been established, Phase Two could begin. During this phase, the aim was to create and implement the database in both an Excel toolkit and a paper guide.

The first step of creating the paper guide was to perform a comparison of the different formats for the structure of the Highway Code, determining the most suitable. Next, a standardised format was created, which the database was implemented in accordance with. Once the data had been inputted and formatted correctly, a validation process was initiated. To illustrate the outcome of the validation process, determining if the paper guide is 'fit for use', a decision block is used. This can be seen in figure 1. If yes – the Highway Code paper guide is finished – otherwise, the issues are addressed, and repeatedly sent back to validation until deemed solved.

For the Excel toolkit, the first step was to choose a software development methodology. As the choice fell upon combining a spiral methodology with a trial and error approach, the next process that followed was creating the list of requirements with the features needed for the functionality of the toolkit. Next, a risk assessment was performed, where potential risks were identified and addressed through proposed solutions.

From the risk assessment, the actual implementation is done. This includes developing and testing/validating the features, ensuring they correspond with the intended user's expectations and requirements, as well as that there are no bugs in the features. This stage in the process is illustrated in figure 1 with a choice block, where either the features are validated, resulting in a finished toolkit – otherwise, similar to the paper guide process, the bugs are solved and sent back for validation until deemed solved.

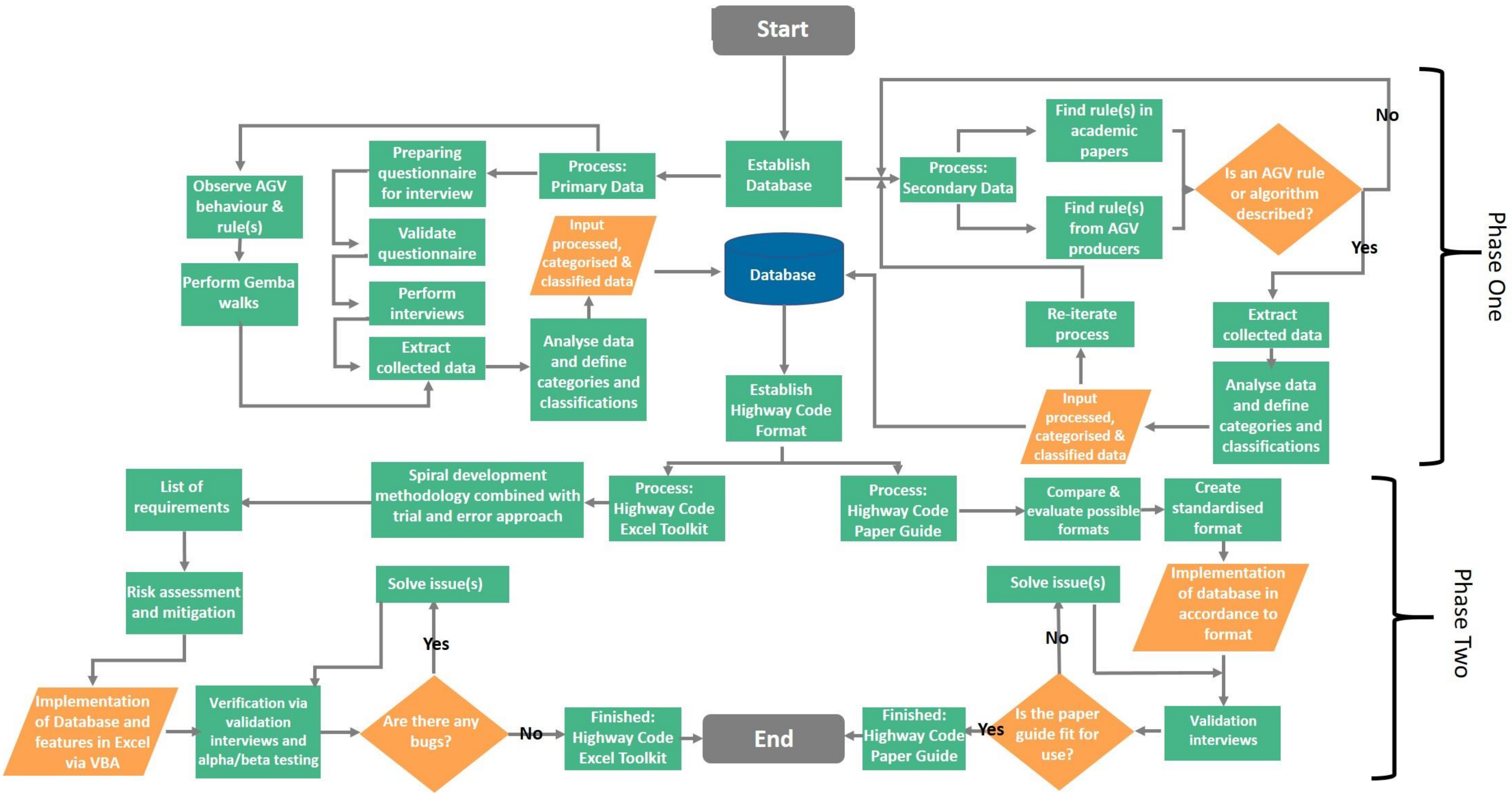


Figure 1 - Flowchart of the methodology process for constructing the Highway Code

A brief overview of an AGV and how they work

In this section, a brief overview of how an AGV functions and the different areas that affect the deterministic rules of an AGV. For simplicity, the section is divided into four sub-sections.

Types of AGVs

Whilst there are some core features, the mechanics of an AGV is very much dependent on the type of vehicle. Some of the most common vehicles types are: masted vehicles, unit load vehicles, tow vehicles, carts vehicles and custom vehicles. (MHI, 2012). In this paper, the differences between these five types will be discussed, providing a basic understanding of how the different types of AGVs function.

Masted vehicles

The masted vehicle is one of the most flexible types of AGVs. With features such as the outrigger and the reach, which can be seen in figure 2, it resembles a standard manual lift truck. A major benefit with the masted vehicle is that it's compatible with a variety of tasks. This allows it to perform everything from block stacking to stand and conveyers. However, the vehicle type is somewhat restricted in terms of the size of the object it's carrying, making it, for example, less suitable to move objects with considerable width. (MHI, 2012).

Unit load vehicles

Different to the masted vehicle, the unit load vehicle is positioned under the objects it's carrying, allowing the vehicle to be designed more compactly. This, in turn, allows the unit load vehicle to carry a variety of objects in various shapes and sizes. Nevertheless, a considerable weakness with the unit load vehicle is its load handling ability. More than often, the unit load vehicle may be unable to load and unload itself, requiring external assistance, e.g. manual workers or cranes. In certain cases, the unit load vehicle is equipped with a conveyor or a lift, positioned on top of the vehicle. However, even in these cases, the capacity is still often limited. (MHI, 2012).

Tow vehicles

Tow vehicles are useful in situations when several parts need to be transported simultaneously. Carrying between one to three carts at once, the tow vehicle can provide significant economic benefits, as it can reduce the number of AGVs needed in the production. The downside with this type of vehicle is the constraint on manoeuvrability the carts inflict. In addition to this, the load and unloading processes require external input, in the form of either manual workers or machinery. (MHI, 2012).

AGV types

Various AGV types

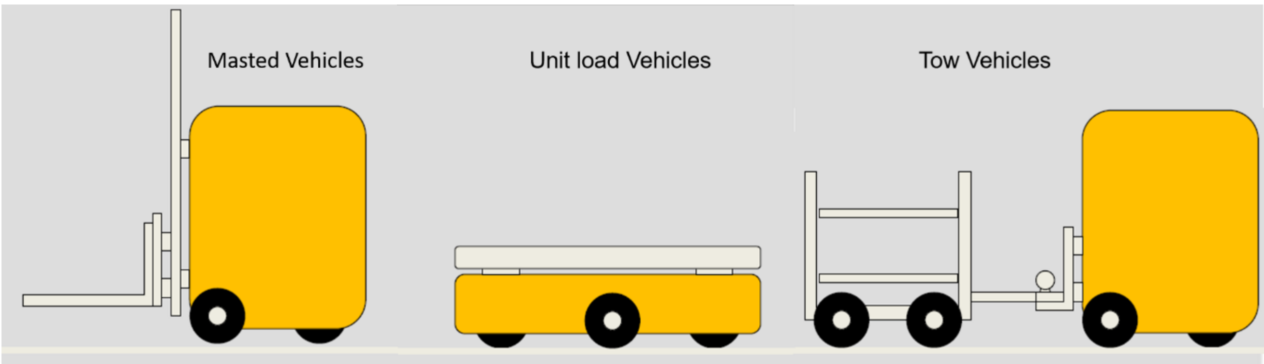


Figure 2 - Illustration of the distinct types of AGV's taken from (MHI, 2012)

Source: MHI (2012)

Cart vehicles

A cart vehicle also referred to as an Automatic Guided Cart (AGC), is simple to its construction and often made for carrying lighter loads. The vehicle navigates using either an inertial or magnetic tape system, creating a type of looping road system. Like the tow vehicle, the cart vehicle faces the same manoeuvrability constraint. (MHI, 2012).

Custom vehicles

Much like the name reveals, the custom vehicle type focuses on customisation, e.g. carrying a specific type of load. They are commonly used for moving work-in-progress (WIP) within the production process. The focus on customisation is both a strength and a weakness. Whilst the utility of a custom vehicle can be optimised for a particular task, it may also create a lock-in situation, where the customised AGVs cannot be used for anything else than the task it's been designed for. (MHI, 2012).

AGV Navigation Systems

The concept of AGV navigation systems has already been touched upon in previous sections, mentioning some of the most common ones being, laser triangulation, inertial, magnetic tape, magnetic grid, natural feature and wire (MHI, 2012).

Laser triangulation navigation system

One of the most popular navigation systems that are currently being used is the laser triangulation system. Using a laser scanner and certain control algorithms, the position of the AGV is determined through triangulation via reflective targets which are spread around within the facility. (MHI, 2012).

Inertial navigation system

The Inertial navigation system uses three types of sensors (Encoder, Accelerometer, and Gyroscope) to calculate the AGVs position, direction, and velocity, using a dead-reckoning methodology (Kim et al, 2012). In relation to AGVs, the system may also be paired with magnetic reference points, which are placed at specific X, Y coordinates beneath the floor. These reference points are then detected via the sensors, which allows it to understand it's travelled distance (via the encoder), it's heading (via the gyroscope) and its speed (via the accelerometer). All of which are maintained through continuous feedback. (MHI, 2012).

Magnetic tape navigation system

Being one of the earliest developed systems, the magnetic tape navigation system uses magnetic tape placed on the floor, creating a path for the AGV. Once the constructed path is finished, an AGV, equipped with a sensor underneath it, can detect the tape, enabling it to navigate along the taped path. (MHI, 2012).

Grid navigation system

Using reference points and the same three types of sensors, the grid navigation system functions similar to the inertial navigation system. The difference, however, between the two systems is the placement of the reference points. Whilst the inertial system places the points in a pre-determined pathway, the grid navigation system places them in a grid pattern, creating a wider area for the AGV to manoeuvre. (MHI, 2012).

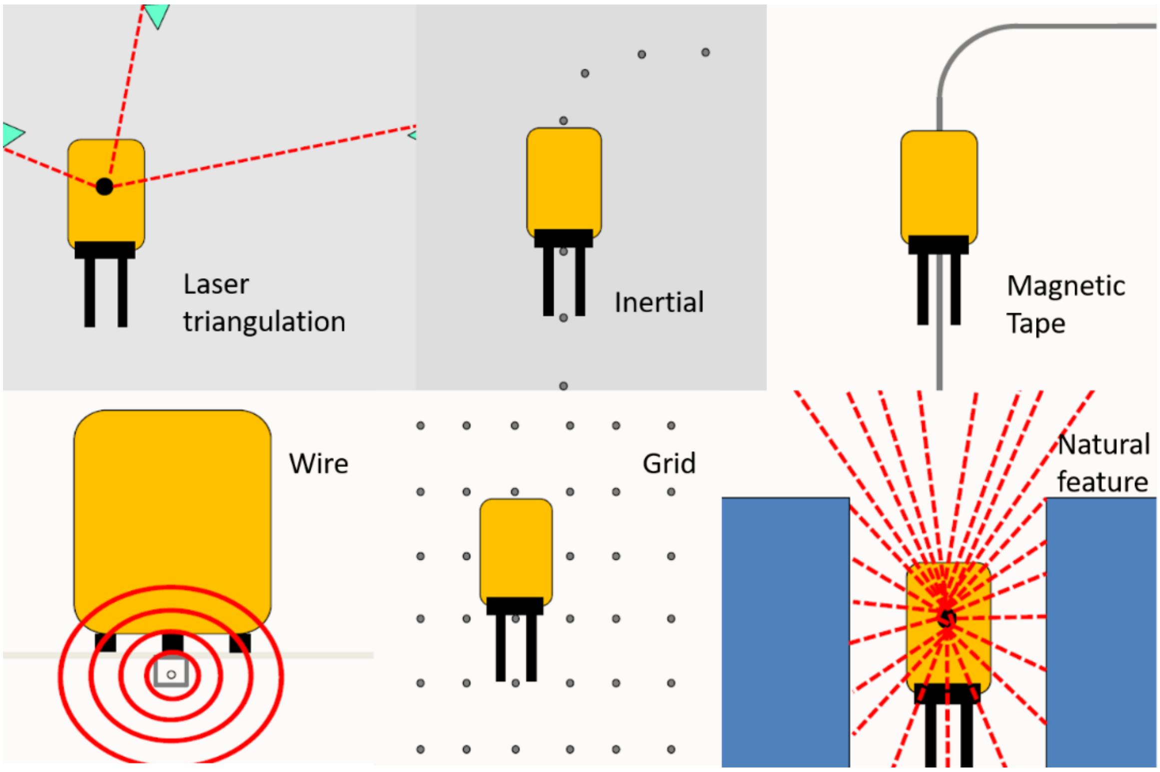


Figure 3 - Illustration of the types of AGV Navigation Systems taken from (MHI, 2012)

Source: MHI (2012)

AGV navigation systems

Various systems for AGV navigation

Natural feature navigation system

Stored in its memory, the natural feature navigation system uses images of the area in which the AGV operates in, as a reference. From these images, the natural feature navigation system can identify features in the operating environment that are reoccurring. By comparison, the system can then allow the AGV to calculate its relative position to its reference image. The recording and identification are usually done either by laser or camera. (MHI, 2012).

Wire navigation system

The final system that will be discussed, is the wire navigation system. Much like the name reveal, the system navigates using a wire which is placed underneath the floor. Through a combination of antennas and encoders, the AGV is able to locate the wired pathway and calculate its distance. (MHI, 2012).

Manoeuvrability

Non-Holonomic

Being one of the more common configurations amongst AGV types, both the tricycle and the differential drive utilises a three-wheel structure, with two wheels in the front and one centrally placed in the back. The structure allows for a certain amount of flexibility in terms of movement, and as seen in figure 5, both types scored a two between the degree of mobility and steerability. This signals that the flexibility is dependent on the AGVs path, making them non-holonomic. (MHI, 2012). The difference between the configurations is the back wheel, which has been replaced with an uncontrollable spherical wheel for the differential configuration, giving it an increased capacity to rotate. Legius, Nijmeijer & Rodriguez (2014).

AGV drive configuration

Various AGV configuration

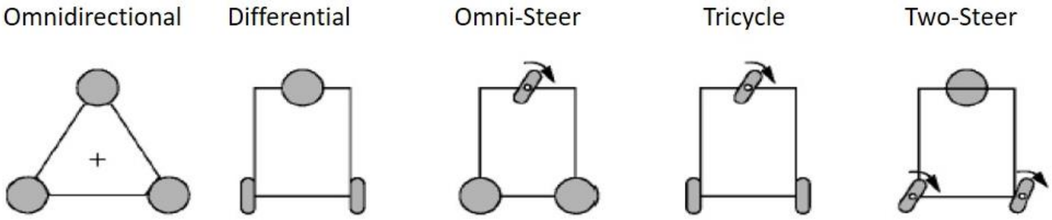


Figure 4 - Illustration of Degree of Manoeuvrability for different types of drive configuration taken from (Legius, Nijmeijer & Rodriguez, 2014)

Source: Legius, Nijmeijer & Rodriguez (2014)

Holonomic

The omnidirectional, Omni-steer and two-steer configurations are all holonomic, with a score of three. This means that the relationship between the controllable and total degree of freedom is in parity, which allows the AGV to manoeuvre independently, regardless of the path it's taking in any direction and from any position. Whilst this is partially achieved through the drive configuration, the wheels are also a critical component, which can be seen in figure 5. Legius, Nijmeijer & Rodriguez (2014).

AGV wheels

Various AGV wheels

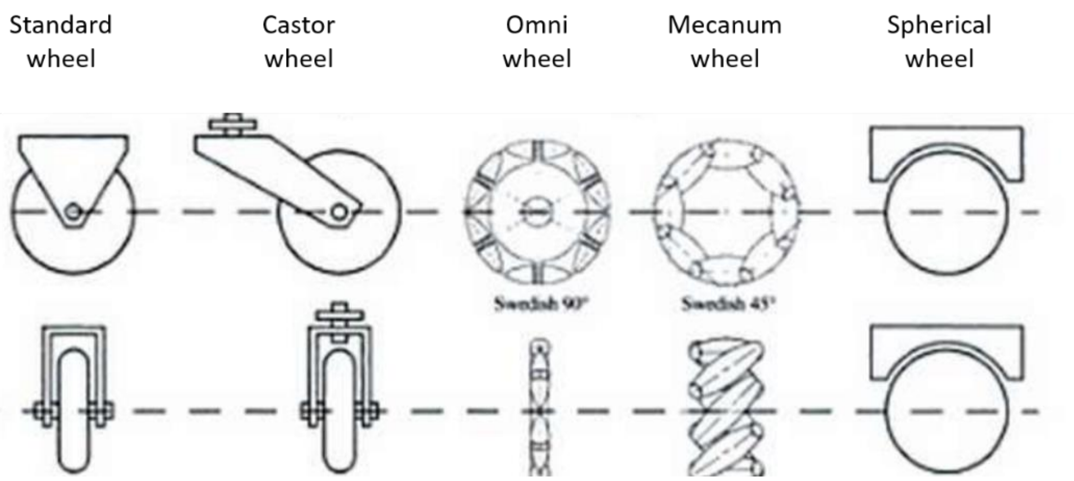


Figure 5 -- Illustration of Degree of Manoeuvrability and wheels (Legius, Nijmeijer & Rodriguez, 2014)

Source: Legius, Nijmeijer & Rodriguez (2014)

Obstacle Detection

Through the previous three subsections, this paper has managed to cover several important concepts for understanding the basic mechanics of an AGV. However, to complete the basics, the concept of obstacle detection, and how an AGV avoids driving into obstacles needs to be elaborated on. To do this, two methods will be discussed: Laser obstacle detection, and mechanical bumpers.

Laser obstacle detection

By equipping the AGV with safety rated laser sensors, it can detect objects that are in its path allowing it to avoid possible impacts. The lasers field is split into two zones: the warning zone and the stop zone, the latter one being the smaller in terms of size out of the two. To maintain a prominent level of protection, the size of the field continuously changes. When the AGV accelerates, the field is expanded to cover a larger area, when it slows down, it narrows the field, and when the AGV is turning, it shifts into an asymmetrical shape. If an obstacle enters the warning zone, the AGV will slow down and sometimes also signal through a sound horn that it has detected the obstacle. If the obstacle enters the stop zone, the AGV will stop completely and may need manual intervention, depending on the situation. (MHI, 2012).

Mechanical bumpers

The mechanical bumper system relies on a limit switch, which stops the AGV when the bumper material gets compressed, i.e. through physical impact. The strength of this type of obstacle detection system is that it is less affected by its surrounding, e.g. dust on the ground, unlike the laser system. However, once an impact has been detected, the bumper material needs replacing, requiring both time and effort. (MHI, 2012).

List of regulations

Another important aspect for the understanding how an AGV functions, is the safety and regulations that the robot needs to comply with. These are obligations that the AGV needs to abide, to ensure that they are safe to operate within a specific environment. In total, 27 safety compliances, standards and regulations were identified, all somehow related to AGVs. The identification process began by looking for keywords, such as “Industrial robots”, “robots”, “driverless”, and “machinery”, on a set of standards and regulations provided from Airbus’ internal database. Using these keywords, various standards and regulations were found, which oftentimes also suggested further standards and regulations to explore.

Table 1 presents the total list of standards and regulations that the AGVs may have to comply with. Readers should be made aware, that AGV producers may not account for all the identified standards and regulations, as some of them are very much dependent on how the AGV functions, and what type of mechanism the AGV has at its disposal.

Table 1 - List of applicable standards and regulation for AGVs

Name	Definition	Edition
BS EN ISO 14539	**Manipulating industrial robots:** Object handling with grasp-type grippers - Vocabulary and presentation of characteristics	2002
2006/42/EC	**Machinery Directive:** machinery, and amending Directive 95/16/EC (recast)	2006
BS ISO 9787	**Robots and robotic devices:** Coordinate systems and motion nomenclatures	2015
ISO 9283	**Manipulating industrial robots:** Performance criteria and related test methods	1998
2004/108/EC	**EMC Directive:** the approximation of the laws of the Member States relating to electromagnetic compatibility and repealing.	2004
EN 61000-6-2	**Electromagnetic compatibility (EMC):** Part 6-2: Generic standards; Immunity for industrial environments	2005
EN 61000-6-4 + A1	**Electromagnetic compatibility (EMC):** Part 6-4: Generic standards; Emission standard for industrial environments	2011
ISO/TS 15066	**Robots and robotic devices:** Collaborative robots	2016
EN 60204-1 + A1	**Safety of machinery:** Electrical equipment of machines - Part 1: General requirements	2009
DIN EN 1175-1	**Safety of industrial trucks:** Electrical requirements	2011
DIN EN 1525	**Safety of industrial trucks:** Driverless trucks and their systems	1997
DIN EN 1526	**Safety of industrial trucks:** Additional requirements for automated functions on trucks	2009

Name	Definition	Edition
EN ISO 8373	**Robots and robotic devices:** Vocabularity	2012
EN ISO 10218-1	**Industrial robots:** Safety	2011
BS EN ISO 10218-2	**Robots and robotic devices:** Safety requirements for industrial robots. Robot systems and integration	2011
EN ISO 12100	**Safety of machinery:** General principles of design, risk assessment and risk reduction	2010
EN ISO 13849-1	**Safety of machinery:** Safety-related parts of control systems - Part 1: General principles of design	2008
EN ISO 13849-2	**Safety of machinery:** Safety-related parts of control systems - Part 2: Validation	2012
EN ISO 13850	**Safety of machinery:** Emergency stop - Principles for design	2008
BS EN ISO 9946	**Manipulating industrial robots:** Presentation of characteristics	1999
BS EN ISO 11593	**Manipulating industrial robots:** Automatic end effector systems. Vocabulary and presentation of characteristics	1998
EN ISO 13855	**Safety of machinery:** Positioning of safeguards with respect to the approach speeds of parts of the human body	2010
DIN ISO 2806	**Industrial automation systems:** Numerical control of machines - Vocabulary	1996
ISO 230-2	**Test code for machine tools:** Part 2: Determination of accuracy and repeatability of positioning of numerically controlled axes	2014
ISO 230-2 AMD 1	**Test code for machine tools:** Part 2: Determination of accuracy and repeatability of positioning of numerically controlled axes; Amendment 1	2016
ISO 230-4	**Test code for machine tools:** Part 4: Circular tests for numerically controlled machine tools	2005
ISO 6983-1	**Automation systems and integration:** Numerical control of machines - Program format and definitions of address words - Part 1: Data format for positioning, line motion and contouring control systems	2009
ISO 10791-7	**Test conditions for machining centres:** Part 7: Accuracy of finished test pieces	2014

Source: Hedborg (2017)

Dispatchment

In this section, the category of 'Dispatchment' will be discussed, focusing on AGV rules for pickup, delivery and order assignments.

1

Random Vehicle (RV)

Under this rule, the pickup task is randomly assigned to any available operational vehicle.

- Accounts for AGV and other AGV; set of AGV mapped to itself
- Source: Characterization of automatic guided vehicles dispatching rules by Egbelu & Tanchoco (1984)

2

Nearest Vehicle (NV)

Under this rule, travelling speed and computed travel distance determines the nearest vehicles for pickup task.

- Accounts for AGV and other AGV; set of AGV mapped to itself
- Source: Characterization of automatic guided vehicles dispatching rules by Egbelu & Tanchoco (1984)

3

Farthest Vehicle (FV)

Under this rule, travelling speed and computed travel distance determines the farthest vehicles for pickup task.

- Accounts for AGV and other AGV; set of AGV mapped to itself
- Source: Characterization of automatic guided vehicles dispatching rules by Egbelu & Tanchoco (1984)

4 Longest Idle Vehicle (LIV)

Under this rule, highest dispatching priority is given to the longest idle vehicle since last assignment.

- Accounts for AGV and other AGV; set of AGV mapped to itself
- Source: Characterization of automatic guided vehicles dispatching rules by Egbelu & Tanchoco (1984)

5 Most Cumulative Idle Vehicle (MIT)

Under this rule, highest dispatching priority is given to the vehicle with most cumulative idle time.

- Accounts for AGV and other AGV; set of AGV mapped to itself
- Source: The Selection of the Best Control Rule for a Multiple-Load AGV System Using Simulation and Fuzzy MADM in Flexible Manufacturing System by Azimi, Haleh & Alidoost (2010)

6 Least Cumulative Idle Time (LIT)

Under this rule, highest dispatching priority is given to the vehicle with least cumulative idle time.

- Accounts for AGV and other AGV; set of AGV mapped to itself
- Source: The Selection of the Best Control Rule for a Multiple-Load AGV System Using Simulation and Fuzzy MADM in Flexible Manufacturing System by Azimi, Haleh & Alidoost (2010)

7 Least Utilised Vehicle (LUV)

Under this rule, highest dispatching priority is given to the vehicle with least utility in terms of material handling.

- Accounts for AGV and other AGV; set of AGV mapped to itself
- Source: Characterization of automatic guided vehicles dispatching rules by Egbelu & Tanchoco (1984)

8 First Available Vehicle (FAFS)

Under this rule, the first available vehicle is dispatched to requesting work centre.

- Accounts for AGV and other AGV; set of AGV mapped to itself
- Source: The Selection of the Best Control Rule for a Multiple-Load AGV System Using Simulation and Fuzzy MADM in Flexible Manufacturing System by Azimi, Haleh & Alidoost (2010)

9 Random Work Centre (RW)

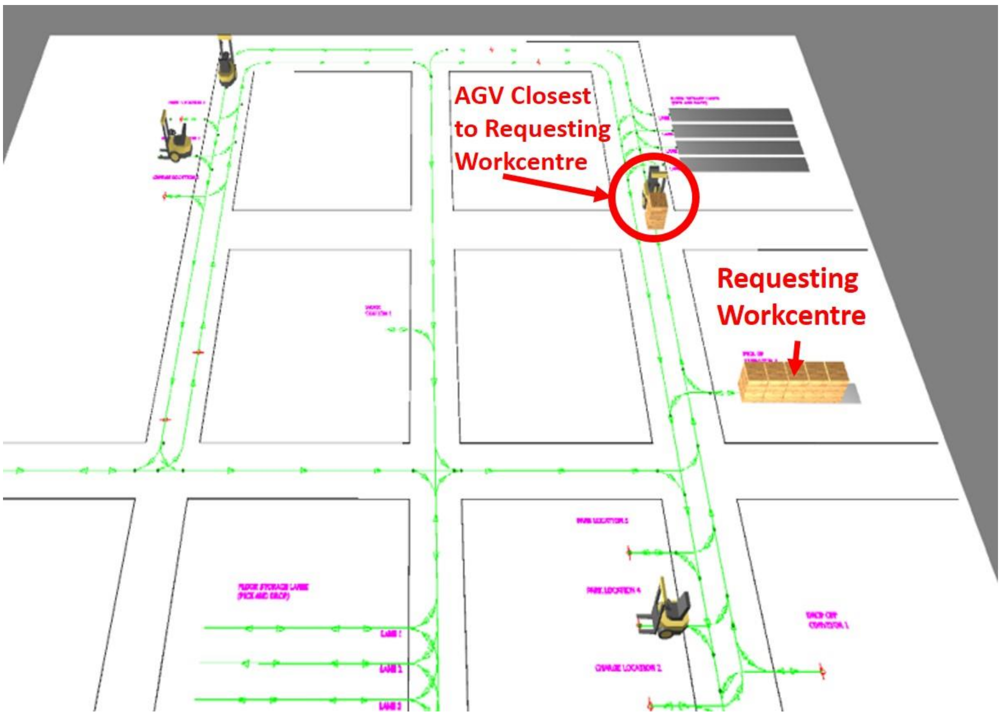
Under this rule, available vehicles are dispatched to a randomly selected work centre.

- Accounts for AGV and other AGV; set of AGV mapped to itself
- Source: Characterization of automatic guided vehicles dispatching rules by Egbelu & Tanchoco (1984)

10 Shortest Travel Time / Distance (STT/D)

Under this rule, travelling speed and computed travel distance determines the nearest vehicles for work centre pickup task.

- Accounts for AGV and other AGV; set of AGV mapped to itself
- Source: Characterization of automatic guided vehicles dispatching rules by Egbelu & Tanchoco (1984)



Rule 10

AGV closest to requesting work centre is dispatched

Figure 6 – Illustration of the shortest travel time / distance rule

Source: Hedborg (2017)

11 Longest Travel Time / Distance (LTT/D)

Under this rule, travelling speed and computed travel distance determines the farthest vehicles for work centre pickup task.

- Accounts for AGV and other AGV; set of AGV mapped to itself
- Source: Characterization of automatic guided vehicles dispatching rules by Egbelu & Tanchoco (1984)

12 Maximum Outgoing Queue Size (MOQS)

Under this rule, the vehicle is assigned to the work centre with the maximum number of unit loads in its output inventory.

- Accounts for AGV and other AGV; set of AGV mapped to itself
- Source: Manufacturing Facilities: Location, Planning, and Design by Sule (2008)

13 Maximum Remaining Outgoing Queue Space (MROQS)

Under this rule, the vehicle is assigned to the work centre with least remaining space for outgoing inventory.

- Accounts for AGV and other AGV; set of AGV mapped to itself
- Source: Manufacturing Facilities: Location, Planning, and Design by Sule (2008)

14 First Come-First Serve (FCFS)

Under this rule, the vehicle is assigned to departments in sequential chronological order, based on requests.

- Accounts for AGV and other AGV; set of AGV mapped to itself
- Source: Manufacturing Facilities: Location, Planning, and Design by Sule (2008)

15 Smallest-Remaining-Processing-Time (SRPT)

Under this rule, the vehicle with the least calculated remaining processing time left is assigned to the delivery task.

- Accounts for AGV and other AGV; set of AGV mapped to itself
- Source: A simulation study on the performance of task-determination rules and delivery-dispatching rules for multiple-load AGVs by Ho & Chien (2004)

16 Micro-Opportunistic Scheduling Algorithm (MOSA)

This algorithm accounts for both critical jobs and travel time of vehicles to determine the vehicle most suitable to carry out the order.

- Accounts for AGV and other AGV; set of AGV mapped to itself
- Source: Scheduling and Routing Algorithms for AGVs : a Survey by Ling & Jing (1999)

17 Combination (CM)

This algorithm combines NV & SRPT. The vehicle is assigned based on both its remaining processing time and the distance of the task in regard to the current position of the vehicle.

- Accounts for AGV and other AGV; set of AGV mapped to itself
- Source: A simulation study on the performance of task-determination rules and delivery-dispatching rules for multiple-load AGVs by Ho & Chien (2004)

18 Modified First Come-First Serve (MFCFS)

Under this rule, the vehicle is assigned to work centres in sequential chronological order, based on requests. Work centres cannot place more than one request. Number of assignment made to a work centre is related to the respective job traffic intensity in that work centre.

- Accounts for AGV and other AGV; set of AGV mapped to itself
- Source: Characterization of automatic guided vehicles dispatching rules by Egbelu & Tanchoco (1984)

19 Unit Load Shop Arrival Time (ULSAT)

Under this rule, vehicles are assigned in an order of entry to reduce the time jobs or unit loads spend in the shop is minimised.

- Accounts for AGV and other AGV; set of AGV mapped to itself
- Source: Characterization of automatic guided vehicles dispatching rules by Egbelu & Tanchoco (1984)

20 Entrance Control (EC)

Under this rule, vehicles are assigned based on net-stocks of vehicles at stations (number of vehicles in the storage area of the station, the number of vehicles traveling between a decision point and the pickup station and number of loads waiting at the station) in order to increase the availability of vehicles at stations.

- Accounts for AGV and other AGV; set of AGV mapped to itself
- Source: Design and performance analysis of multistation automated guided vehicle systems by Talbot (2003)

21 Multi-attribute dispatching (Multi-Att)

Under this rule, vehicles are assigned based on the vehicle requirement at a specific station and travel distance from the vehicles current position to the pickup station.

- Accounts for AGV and other AGV; set of AGV mapped to itself
- Source: Multi-attribute dispatching rules for AGV systems with many vehicles by Le-Ahn & De Koster (2004)

22 Delivery-Task First (DTF)

Under this rule, vehicles always prioritise the task of delivery, even if both pickup and delivery tasks are available. A vehicle will continue performing delivery tasks if there are loads on it.

- Accounts only for itself "AGV"
- Source: A simulation study on the performance of task-determination rules and delivery-dispatching rules for multiple-load AGVs by Ho & Chien (2004)

Rule 22

AGV will prioritise delivery tasks (red line) before pursuing any other task (blue line)

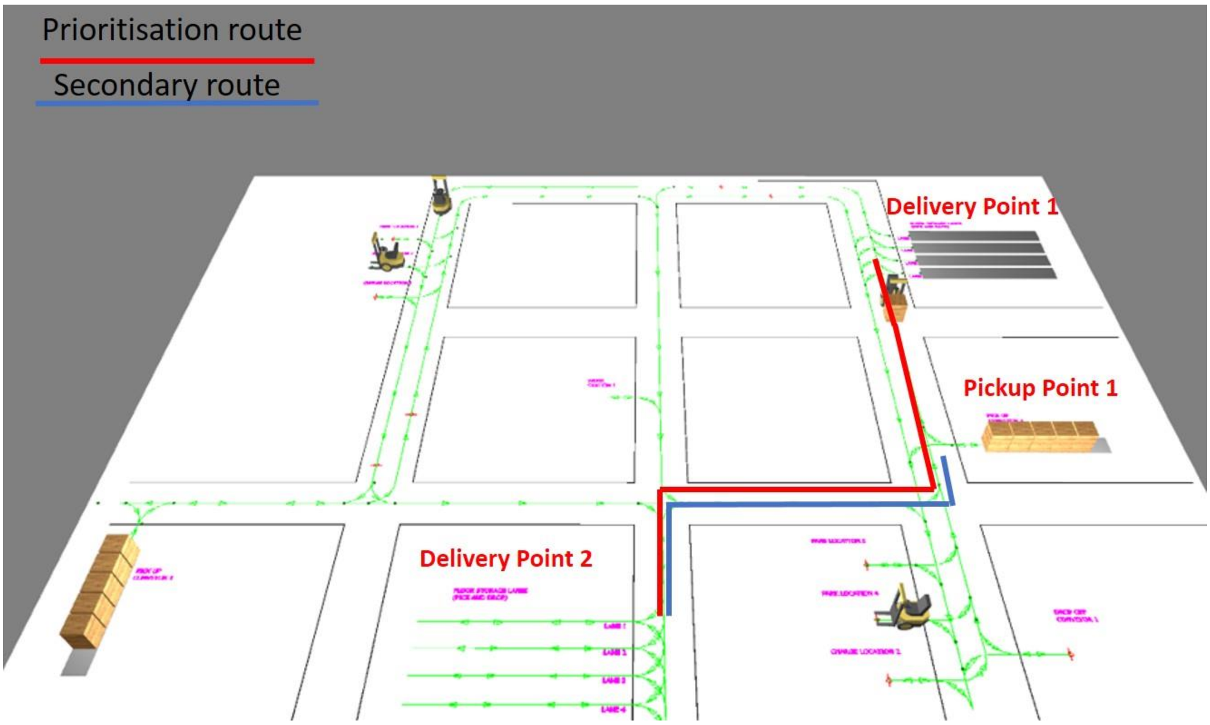


Figure 7 - Illustration of the delivery-task first rule

Source: Hedborg (2017)

23 Vehicle Looks For Work (VLFW)

Under this rule, the vehicle will look for the demand and choose next pickup task that is closest to its position.

- Accounts only for itself "AGV"
- Source: Simulation Yodel Calculates How Many Automated Guided Vehicles are Needed by Newton (1985)

24 Maximum Demand (MD)

Under this rule, vehicles will prioritise pickup stations based on the maximum demand for that station.

- Accounts only for itself "AGV"
- Source: The Selection of the Best Control Rule for a Multiple-Load AGV System Using Simulation and Fuzzy MADM in Flexible Manufacturing System by Azimi, Haleh & Alidoost (2010)

25 Pickup-Task First (PTF)

Under this rule, vehicles always prioritise the task of pickup, even if both pickup and delivery tasks are available. A vehicle will continue performing delivery tasks if there are loads on it.

- Accounts only for itself "AGV"
- Source: A simulation study on the performance of task-determination rules and delivery-dispatching rules for multiple-load AGVs by Ho & Chien (2004)

26 Load-Ratio (LR)

Under this rule, load ratio weighs delivery task against pickup tasks and dispatches vehicle accordingly.

- Accounts only for itself "AGV"
- Source: A simulation study on the performance of task-determination rules and delivery-dispatching rules for multiple-load AGVs by Ho & Chien (2004)

Load-Selection

In this section, the category of 'Load-Selection' will be discussed, focusing on AGV rules for how an AGV chooses to prioritise different loads, both in terms of pickup and delivery.

27 Shortest Distance (SD)

Under this rule, vehicles calculate the distance between the delivery point and the object to-be delivered, choosing the least distance as its next delivery point.

- Accounts for AGV and other AGV; set of AGV mapped to itself
- Source: A simulation study on the performance of task-determination rules and delivery-dispatching rules for multiple-load AGVs by Ho & Chien (2004)

28 Smallest-Input-Queue (SIQ)

Under this rule, vehicles choose their next delivery point with the least amount of load queue.

- Accounts only for itself "AGV"
- Source: A simulation study on the performance of task-determination rules and delivery-dispatching rules for multiple-load AGVs by Ho & Chien (2004)

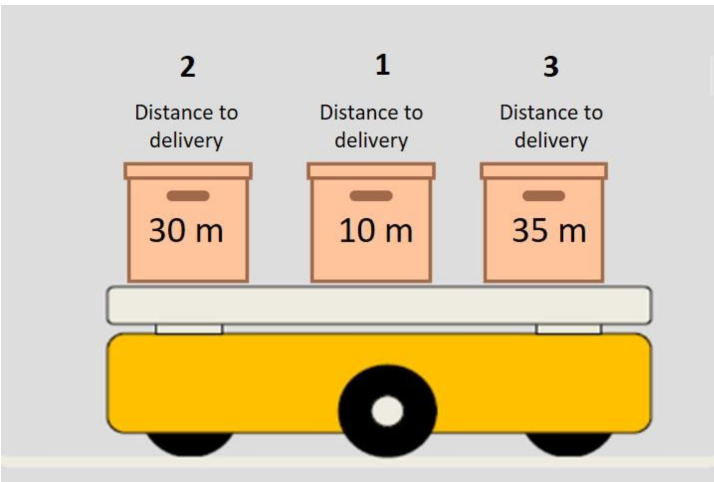


Figure 8 - Illustration of the shortest distance rule

Source: Hedborg (2017)

Rule 27

AGV chooses to deliver the load with least distance. The numbers show the order the AGV will delivery it's objects

29 First-In-Queue-First-Out (FIQFO)

Under this rule, the vehicle will prioritise the load with the longest waiting time for delivery.

- Accounts only for itself "AGV"
- Source: The Selection of the Best Control Rule for a Multiple-Load AGV System Using Simulation and Fuzzy MADM in Flexible Manufacturing System by Azimi, Haleh & Alidoost (2010)

30 Last-in-Queue-First-Out (LIQFO)

Under this rule, the vehicle will prioritise the load with least waiting time for delivery.

- Accounts only for itself "AGV"
- Source: The Selection of the Best Control Rule for a Multiple-Load AGV System Using Simulation and Fuzzy MADM in Flexible Manufacturing System by Azimi, Haleh & Alidoost (2010)

31 Longest-Time-In-System (LTIS)

Under this rule, the vehicle chooses the load with the longest time in the system as next delivery task.

- Accounts only for itself "AGV"
- Source: A simulation study on the performance of task-determination rules and delivery-dispatching rules for multiple-load AGVs by Ho & Chien (2004)

32 Longest-Time-On-Vehicle (LTOV)

Under this rule, vehicles calculate the time of each individual object to-be delivered, picking the object with the longest time on the vehicle as next delivery point.

- Accounts only for itself "AGV"
- Source: A simulation study on the performance of task-determination rules and delivery-dispatching rules for multiple-load AGVs by Ho & Chien (2004)

33 Earliest-Due-Time (EDT)

Under this rule, vehicles calculate the due time of each individual object to-be delivered, picking the object with the earliest due time as next delivery point.

- Accounts only for itself “AGV”
- Source: A simulation study on the performance of task-determination rules and delivery-dispatching rules for multiple-load AGVs by Ho & Chien (2004)

34 Longest-Elapsed-Time-Since-Last-Arrival (LET)

Under this rule, vehicles calculate at what time each individual object to-be delivered last arrived at all possible delivery points, selecting the one with the longest elapsed time for the objects.

- Accounts only for itself “AGV”
- Source: A simulation study on the performance of task-determination rules and delivery-dispatching rules for multiple-load AGVs by Ho & Chien (2004)

35 Smallest-Slack-Time (SST)

Under this rule, the vehicle chooses loads with the least slack-time for next delivery. Slack-time is calculated for each individual object to-be delivered, taking the due time of the load and reduce it by current time of the system for the load and the remaining processing time of the load.

- Accounts only for itself “AGV”
- Source: A simulation study on the performance of task-determination rules and delivery-dispatching rules for multiple-load AGVs by Ho & Chien (2004)

36 Random (RDM)

Under this rule, the vehicle chooses a random object to-be delivered for its next delivery point.

- Accounts only for itself “AGV”
- Source: A simulation study on the performance of task-determination rules and delivery-dispatching rules for multiple-load AGVs by Ho & Chien (2004)

37 First-Encountered-First-Served (FEFS)

Under this rule, the vehicle will pick up the first load encountered and deliver it first.

- Accounts only for itself "AGV"
- Source: Decentralized control of automated guided vehicles on a simple loop by Bartholdi & Platzman (1989)

Rule 37

AGV delivers its object and moves on to the next object that has been picked up.

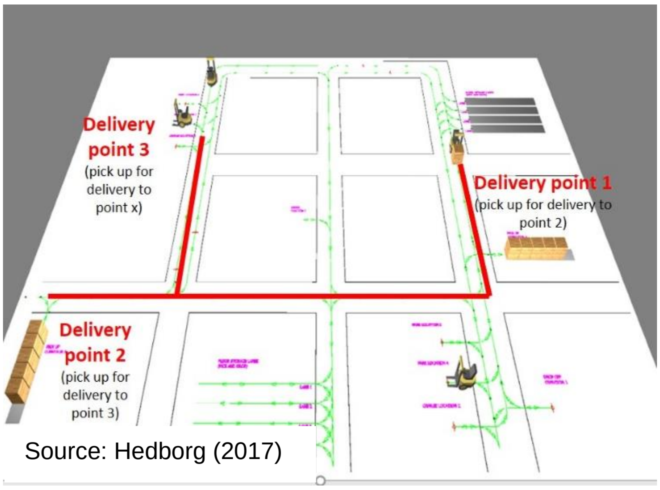


Figure 9 - Illustration of the first-encountered-first-served rule

38 Fixed-Route-Station-Priority (FS)

Under this rule, assuming that the route cannot be altered, the vehicle begins by comparing if any objects at the pickup point are going to the next station that the vehicle will pass on its route. If yes - the vehicle picks the object up, otherwise the object is skipped.

- Accounts only for itself "AGV"
- Source: Load selection of automated guided vehicles in flexible manufacturing systems by Lee, Tangjarukij & Zhu (1996)

39 Fixed-Route-Part-Priority (FP)

Under this rule, the vehicle, assuming that the route cannot be altered, the vehicle only picks up an object if it's going to any of the destinations passed by in its delivery route, otherwise the object is skipped.

- Accounts only for itself "AGV"
- Source: Load selection of automated guided vehicles in flexible manufacturing systems by Lee, Tangjarukij & Zhu (1996)

40 Identical-Destination (ID)

Under this rule, the vehicle begins by comparing if any objects at the pickup point are going to the same delivery point as it's current to-be delivered objects. If yes - the vehicle will pick these up. Otherwise, the vehicle will check if it has empty space left, deploying a first-in-first-out rule to pick up the object in the queue.

- Accounts only for itself "AGV"
- Source: A simulation study on the performance of task-determination rules and delivery-dispatching rules for multiple-load AGVs by Ho & Chien (2004)

41 Pick-All-Send-Nearest (PN)

Under this rule, the vehicle will continuously pick up objects until all space is utilised. For every object picked up, the pathway of the vehicle is re-calculated and the objects with the shortest delivery travel distance are prioritised.

- Accounts only for itself "AGV"
- Source: Load selection of automated guided vehicles in flexible manufacturing systems by Lee, Tangjarukij & Zhu (1996)

42 Variable-Route-Part-Priority (VP)

Under this rule, the route can be altered under the condition that it cannot extend the delivery time to its original delivery point. Objects will therefore only be picked up if they do not interfere with the initial routing. This could result in an initial delivery point being added after the final original delivery point has been reached.

- Accounts only for itself "AGV"
- Source: Load selection of automated guided vehicles in flexible manufacturing systems by Lee, Tangjarukij & Zhu (1996)

43 Variable-Route-Station-Priority (VS)

Under this rule, the route can be altered under the condition that it cannot extend the delivery time to its original delivery point. Objects will therefore only be picked up if they do not interfere with the initial routing. The vehicle does this by comparing if any objects at the pickup point are going to the next station that the vehicle will pass on its route. If yes - the vehicle picks the object up, otherwise the object is skipped.

- Accounts only for itself “AGV”
- Source: Load selection of automated guided vehicles in flexible manufacturing systems by Lee, Tangjarukij & Zhu (1996)

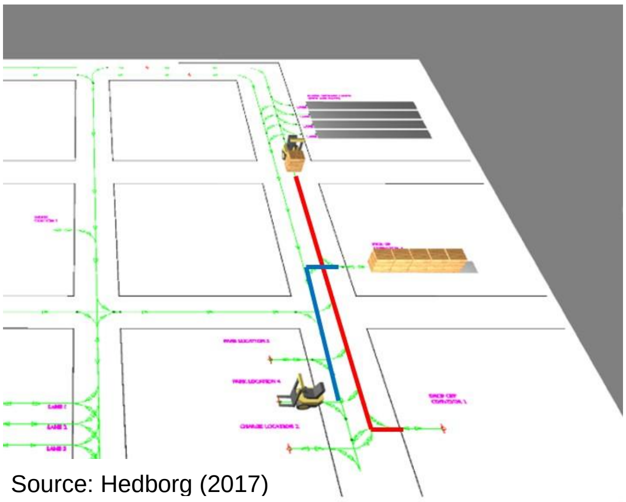
Routing Method

In this section, the category of ‘Routing Method’ will be discussed, focusing on AGV rules for how an AGV determines its route for pickup or/and delivery missions.

44 Greedy Policy/Algorithm (GPA)

Under this rule, the vehicle will attempt to find the shortest distance possible without consideration to anything outside of its programmed environment, such as other vehicles.

- Accounts only for itself “AGV”
- Source: Scheduling and Routing Algorithms for AGVs: a Survey by Ling & Jing (1999)



Rule 44

As seen in the picture the AGV’s will determine their routes regardless of each other making the blue and red lines cross.

Figure 10 - Illustration of the greedy policy/Algorithm rule

45 Time Window (TW)

Under this rule, the vehicles ability to move around is determined by a specific time window.

- Accounts only for itself “AGV”
- Source: Time Windows Based Dynamic Routing in Multi-AGV System by Smolic-Rocak et al (2010)

46 Dijkstra's Shortest Path Algorithm (DSP)

Under this rule, the vehicles path is determined by calculating the occupation time for specific positions for all operative vehicles, which is then compared to avoid potential conflict. Head-to-head conflicts are avoided by the vehicle finding another shortest path with consideration to the occupied space. Head-to-tail conflicts are avoided by deploying a FIFO approach, letting the vehicle who was routed to occupy the space first pass.

- Accounts for AGV and other AGV; set of AGV mapped to itself
- Source: A Note on Two Problems in Connexion with Graphs by Dijkstra (1958)

47 Partitioning Shortest Path (PSP) Algorithm

Under this rule, the vehicles path is determined with consideration to other operative vehicles path, which is assumed to be fixed, making it impossible for two or more vehicles to take the same path.

- Accounts for AGV and other AGV; set of AGV mapped to itself
- Source: Scheduling and Routing Algorithms for AGVs: a Survey by Ling & Jing (1999)

48 Labelling (LBL) Algorithm

Under this rule, the algorithm converts every physical path segment into a node, linking in with two junctions and/or stations and assigns labels with a window time for each node. The vehicle can then compare the time of each labelled node and determine the shortest path for a single AGV.

- Accounts only for itself "AGV"
- Source: Scheduling and Routing Algorithms for AGVs: a Survey by Ling & Jing (1999)

49 Incremental Route Planning (IRP)

Under this rule, using a system of nodes, the pathway of the vehicle is planned incrementally, step by step, by checking the status of the closest nodes to the position of the vehicle and how other vehicles are moving around the network. The node with the shortest travel path is selected and the process reiterates until the destination of the vehicle is reached.

- Accounts for AGV and other AGV; set of AGV mapped to itself
- Source: Scheduling and Routing Algorithms for AGVs: a Survey by Ling & Jing (1999)

50 State-space of Partial Transportation Plans Algorithm (SPPTP)

Under this rule, the algorithm only plans a partial transportation plan for a maximum of two vehicles, defining a state for it. Dynamic programming is then used to find an optimal solution by comparing and identifying the best state.

- Accounts for AGV and other AGV; set of AGV mapped to itself
- Source: Dispatching, Routing, and Scheduling of Two Automated Guided Vehicles in a Flexible Manufacturing System by Langevin, Lauzon & Riopel (1996)

51 Evolutionary Algorithm

Under this rule, the algorithm assumes each vehicle to be a decentralised agent, generating a partial route which is not allowed to interfere with other vehicles. By using the concept of pheromone data trails, the algorithm can use statistical probability to determine if the next partial route candidates are likely to be occupied or not.

- Accounts for AGV and other AGV; set of AGV mapped to itself
- Source: Evolutionary routing method for multi mobile robots in transportation by Konishi et al (2002)

Traffic Regulation

In this section, the category of 'Traffic Regulation' will be discussed, focusing on AGV rules for traffic behaviour and collision avoidance.

52 Improved Ant Colony Algorithm (IAC)

Under this rule, each operative vehicle will release a data pheromone trail which gets stronger the more the trail is used and weakens if not over time, thus allowing for an optimal path to be calculated for other vehicles in the area using statistical probability.

- Accounts for AGV and other AGV; set of AGV mapped to itself
- Source: Study on robot path collision avoidance planning based on the improved ant colony algorithm by Li, et al (2016)

53 Warning/Stop Zone Shutdown (WSZS)

Under this rule, by using features such as camera or sensors, the vehicle can determine the distance of an obstacle. To avoid collision, a 'shutdown' criterion is set, where obstacles cannot be closer than the max distance to the vehicle.

- Accounts for AGV and other AGV; set of AGV mapped to itself
- Source: How do the vehicles work in an AGV system? By MHI (2012)