Multi-Attribute Dispatching Rules For Agv Systems With Many Vehicles

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MULTI-ATTRIBUTE DISPATCHING RULES FOR AGV SYSTEMS WITH MANY VEHICLES

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Abstract

Internal transport systems using automated guided vehicles (AGVs) are widely used in many facilities such as warehouses, distribution centers and transshipment terminals. Most AGV systems use online dispatching rules to control vehicle movements. In literature, there are many types of dispatching rules such as single- and multi-attribute dispatching rules. However, a dispatching rule that is good for all cases does not exist. In this research, we study a specific type of AGV environments which has not received much attention from researchers - AGV systems with many vehicles as can be seen in airport baggage handling systems. We propose two new multi-attribute dispatching rules for this type of environment and compare their performance with that of two of the best dispatching rules in literature. Using simulation we show that the new multi-attribute dispatching rules are robust and perform very well.

Keywords: Online dispatching, AGV system, Destination-coded vehicle

1 Introduction

In environments such as distribution centers, transshipment terminals and production plants guided vehicles are important means to transport loads between internal storage locations (or workstations in manufacturing facilities). Modern guided vehicles travel under control of a shop floor control system (SFC) or a warehouse management system (WMS) without human interferences. Such vehicles are referred to as automated guided vehicles (AGVs). The performance of internal transport systems using AGVs depends on several factors such as guide-path design, estimating the required number of vehicles, vehicle scheduling, idle-vehicle positioning, battery management, vehicle routing and conflict resolution (Van der Meer, 2000; Le-Anh and De Koster, 2004a). The vehicle scheduling system is responsible for managing vehicles efficiently to guarantee a load service level or to serve loads as good as possible. In internal transport environments, exact information about load arrivals is usually only known a little moment in advance, so scheduling vehicles far in advance in these systems is nearly impossible. The best solution is to use online dispatching rules to control vehicles.

An important advantage of vehicle dispatching rules is that they are, in general, simple and easy to use. A vehicle control system using a dispatching rule, controls vehicles' movements based on some intuitive reasoning. In literature, much effort has been spent on improving the quality of vehicle dispatching rules. A best rule for all cases does not exist; however we can find good rules for specific cases. Particularly, among single-attribute dispatching rules, distance-based dispatching rules such as the nearest-vehicle-first rule (NVF) tend to have a good performance in many environments (De Koster et al., 2004). And in general, multi-attribute dispatching rules are more robust than single-attribute dispatching rules (Jeong and Randhawa, 2001).

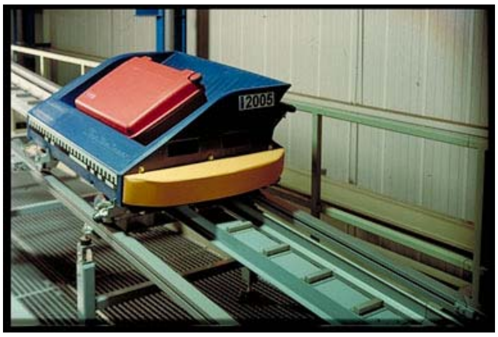

Figure 1 A Destination-Coded Vehicle (courtesy of Vanderlande Industries B.V.)

In this research, we study a particular type of AGV systems – AGV systems with many vehicles (AGVSmV). In such systems, the number of vehicles is much higher than the number of stations. Since there are not enough parking spaces, most idle vehicles have to travel a loop to avoid blocking other vehicles. This type of system is used for baggage handling at airports - baggage handling system (BHS) using destination-coded vehicles. Large airports such as Oslo Gardermoen airport use such baggage handling systems to transport luggage quickly over large distances. Destination-coded vehicles (DCVs) are unmanned carts propelled by linear induction motors mounted to the tracks, which can load and unload bags without stopping. A bag on a DCV has an identification tag and will be sent to its appropriate destination. A DCV can be considered as an automated guide vehicle (AGV) which has a capacity of one piece of luggage (or bag) and may operate at very high speeds (up to 36km/h) (Figure 1). The disadvantages of such BHSs are high investments required for DCVs and their guide-path systems. Figure 2 provides an example of a guide-path system for a BHS using destination-coded vehicles. The system contains rail-track type guide-paths connecting all areas which have transportation requirements.

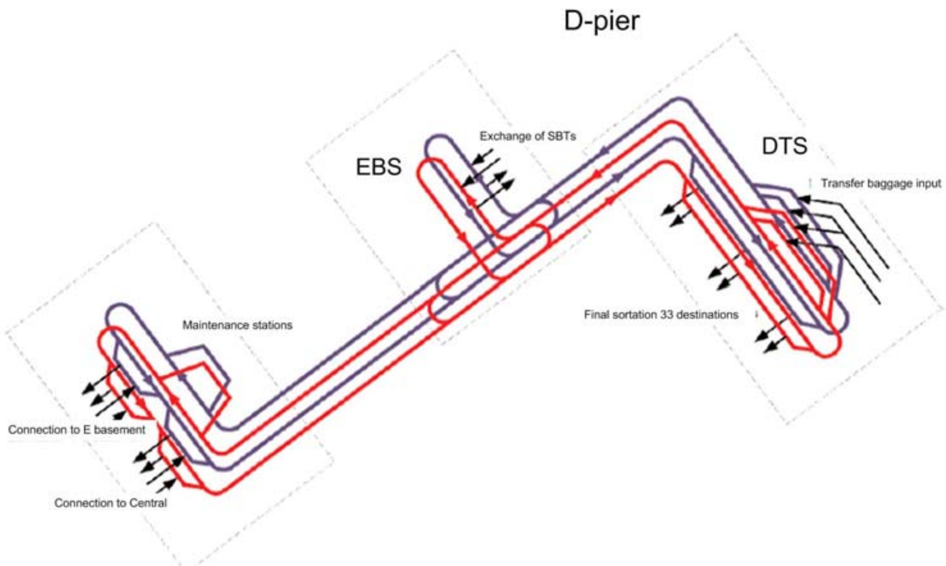

Figure 2 An example of a guide-path system for a BHS using DCVs (courtesy of Vanderlande Industries B.V.)

The literature on AGVSmV is not abundant. We have found only few studies on similar systems (Chevalier et al., 2001; Talbot, 2003). In this research, we propose two new multi-attribute dispatching rules for AGVSmV. We also implement two good online dispatching rules in literature to control vehicles in AGVSmV. These dispatching rules include a shortest-travel-distance-first (STDF) rule (adapted for this type of environment) and the best control rule from Talbot (2003) which is the Entrance Control (EC) rule. Using simulation, we evaluate their performance for two experimental internal transport systems (adapted from Talbot, 2003). We will show that two new multi-attribute dispatching rules (Multi-Att, Multi-Mod) perform very well and are significantly better than STDF. Moreover, the Multi-Att and Multi-Mod rules are more robust than the EC rule. The main contribution of our paper is introducing two new robust and efficient multi-attribute dispatching rules for AGVSmV.

This paper is organized as follows: section 2 studies the literature on online dispatching; section 3 describes dispatching rules used in this paper; section 4 illustrates the case studies and experimental setups; section 5 provides a performance evaluation of dispatching rules. In section 6, we draw conclusions and suggest some directions for future research.

2 Review of literature

Vehicle control systems can be divided into two main categories: decentralized and centralized control systems (Mantel and Landeweerd, 1995; Le-Anh and De Koster, 2004a). The decentralized system dispatches vehicles based on only local information available at the decision moment. The centralized system uses information available at the central controller as well. Although recently, some researches have been devoted to local agent-based vehicle control (Lindeijer, 2003), in practice, due to their efficiency, centralized control systems are more popular. Depending on the ways in which transportation requests are assigned, Egbelu and Tanchoco (1984) have divided dispatching rules into two categories: workstation-initiated dispatching rules (jobs at workstation have the priority to claim vehicles) and vehicle-initiated dispatching rules (vehicles have the priority to claim jobs). Vehicle-initiated dispatching rules prioritize the jobs, according to some specific rules. An idle vehicle selects the job that has the highest priority. Under load-initiated rules, loads have the initiative to claim vehicles using a prioritization rule (vehicles are prioritized for selection). However, once a vehicle finishes a job and has not been claimed by any load, it searches for a load to pickup, using a vehicle-initiated rule.

In operation, a dispatching rule (load- or vehicle-initiated) is invoked at the following events

- Arrival of a new load,
- A vehicle just finishes a job,
- A vehicle is awakened by a load or by another vehicle.

The main difference between the load- and vehicle-initiated dispatching rules is that a load in the system using load-initiated dispatching rules can claim a vehicle. In the system using vehicle-initiated dispatching rules, a vehicle can claim a load but not vice verse.

Dispatching rules can also be classified into single-, multi-attribute and hierarchical dispatching rules or other types of rules such as pre-emptive dispatching rules (Le-Anh and De Koster, 2004a). Single-attribute dispatching rules dispatch vehicles based on only one parameter such as the vehicle empty travel time. Differently, multi-attribute dispatching rules dispatch vehicles based on a multi-attribute dispatching function including more than one parameter. Hierarchical dispatching rules are typical for manufacturing systems where the added value of a part during the manufacturing process is taken into account when the dispatching decision has to be made.

Most dispatching rules described in literature are single-attribute dispatching rules. Some common single-attribute dispatching rules are shortest-travel-distance-first (STDF), first-come-first-served (FCFS), modified-first-come-first-served (MODFCFS), maximum-outgoing-queue-size (MOQS) and minimum-remaining-outgoing-queue-space (MROQS) rules (see Egbelu and Tanchoco, 1984; Egbelu, 1987; Srinivasan et al., 1994; Mahadevan and Narendran, 1994; Sabuncuoglu, 1998). Among single-attribute dispatching rules, distance-based dispatching rules such as STDF tend to have a good performance in many environments, particularly where queues' capacities are not critical (De Koster et al., 2004; Le Anh and De Koster, 2004c).

Klein and Kim (1996) propose several multi-attribute dispatching rules. The dispatching rules presented in their paper are based on the multi-criteria decision making approach. Parameters used in dispatching functions are the vehicle empty travel time, the load waiting time and the queue length. Parameters are normalized to become comparable. Using simulation of two example systems, they show that multi-attribute dispatching rules are superior to single-attribute dispatching rules. Jeong and Randhawa (2001) propose multi-attribute dispatching rules that use three attributes: the vehicle empty travel distance, the remaining space in input buffers and the remaining space in outgoing buffers to decide which load should be transported by a vehicle. They use an additive waiting model to compute weights of member parameters. A neural network is used to dynamically adjust parameters' weights reflecting changes in the system. However, according to their results based on simulation of a sample system, a simple multi-attribute dispatching rule with a good set of weights performs very well and is better in many cases than a multi-attribute dispatching rule with dynamically adjusted weights. They also show that multi-attribute dispatching rules provide a better performance than single-attribute dispatching rules.

Bozer and Yen (1996) introduce two pre-emptive dispatching rules that consider reassignment of moving vehicles. These are modified shortest-travel-time-first (MOD STTF) and bidding-based device dispatching (B^2D^2). The MOD STTF rule is similar to the STTF rule in the sense that it assigns empty vehicles to move requests based on the proximity of the vehicle and the load location, and each vehicle has only one request at a time. The difference is that an empty vehicle may be reassigned to another move request or an empty vehicle may "release" another empty vehicle. If a vehicle travels "uncommitted" to its assigned destination, it may be reassigned to a new arrival request according to some specific conditions (Bozer and Yen, 1996). To some extent, the B^2D^2 rule is similar to the MOD STTF rule, but it is much more complicated. Using a quite extensive simulation study (four layouts and a large set of experimental conditions) Bozer and Yen (1996) show that MOD STTF and B^2D^2 outperform STTF.

In typical baggage or parcel transport systems, the number of vehicles is much higher than the number of stations (or storage areas). In AGVSmV, vehicles' costs are relatively inexpensive in comparison with the total system cost. In AGVSmV, vehicles normally do not have sufficient parking spaces, so we need good dispatching rules which can also take care of many free vehicles. Talbot (2003) proposes some dispatching rules for AGVSmV such as departure and entrance control rules. These dispatching rules perform well for this type of environment. However, the major disadvantage of Talbot (2003)'s dispatching rules is that they are sensitive to the load arrival pattern and the load arrival rate. Therefore, in this study, we propose two new multi-attribute dispatching rules (Multi-Att and Multi-Mod), which are simple, efficient and more robust than Talbot (2003)'s dispatching rules, for AGVSmV. We also adapt one of the best dispatching rules (STDF) in the literature and the Talbot (2003)'s best dispatching rule (EC) for AGVSmV. In the AGVSmV, a dispatching rule is invoked when a vehicle reaches a decision point (Figure 3).

3 Vehicle dispatching rules

For AGVSmV, a good dispatching rule should base on three principles:

- Reducing vehicle (empty) travel distances (time),

- Balancing the system workload (the most "urgent" station has the highest dispatching priority),
- Ensuring availability of vehicles at stations.

Other criteria such as meeting the load due time might be important as well. However, in our experimental case there is no due time for loads. We now introduce dispatching rules used in this study.

(a) Shortest-travel-distance-first rule (STDF)

This dispatching rule aims at reducing the vehicle empty travel time. According to STDF, a released or idle vehicle searches for the closest available load to pickup. The closeness is measured in terms of travel distance. However, we found that the basic implementation of STDF is not working for AGVSmV, therefore we modify STDF as follows:

- When a vehicle find the closest load, this vehicle will be sent to the load pickup location,
- On the way to the assigned load pickup location, if the vehicle passes another decision point, this vehicle might be reassigned to pickup another closer load.

The modified STDF is actually a type of STDF with vehicle reassignment and cancellation.

(b) Entrance Control (EC) dispatching rule (Talbot, 2003)

In this study we implement the best dispatching rule from Talbot (2003). This rule dispatches vehicles based on net-stocks of vehicles at stations aiming at increasing availability of vehicles at stations. The net-stock of vehicles ($s_i(t)$) at station i and time t is calculated as follows:

$$s_i(t) = x_i(t) + y_i(t) - c_i(t)$$

in which

- $s_i(t)$: net-stock of vehicles at station i and time t,
- $x_i(t)$: number of vehicles in the storage area of station i at time t,
- $y_i(t)$: number of vehicles (loaded or empty) traveling on the link between the decision point i and station i at time t,
- $c_i(t)$: number of loads waiting at station i and time t.

The framework of the EC rule

- At the decision point i corresponding to a station i, a vehicle takes the direction to station i if $s_i(t) < S_i$ (a threshold value).
- If the number of vehicles in the vehicle storage area reaches S_i, the station releases an empty vehicle from its internal storage (if any) to the system.

Talbot (2003) has estimated the number of required vehicles and the threshold value (S_i) using a queuing approach. In this research we use these estimated numbers from her study. We adjust these estimated values further using simulation. Practically, a specific set of the threshold values (S_i) is only suitable for a specific case (particularly in unbalanced systems). When the load arrival pattern changes, we have to adapt these values accordingly.

(c) The multi-attribute dispatching rule (Multi-Att)

This rule dispatches vehicles based on a dispatching function associated with two parameters: the vehicle requirement at a specific station and the travel distance from the current vehicle position to the corresponding workstation. This rule aims at both reducing vehicle empty travel time and balancing the workload among stations. The dispatching function is defined as:

$$f_{vi}\left(d,s\right)=\alpha\times d_{vi}+\beta\times s_i$$

$$s_i=\frac{s_i(t)-\min_i s_i(t)}{\max_i s_i(t)-\min_i s_i(t)};\ d_{vi}=\frac{d_{vi}(t)-\min_i d_{vi}(t)}{\max_i d_{vi}(t)-\min_i d_{vi}(t)}$$

- $s_i(t)$: the net-stock of a station i at decision moment t. This value is calculated in the same way as the net-stock of vehicles in Talbot (2003),
- $d_{vi}(t)$: the distance from the vehicle v to the station i at decision moment t,
- max_i, min_i $s_i(t)$: the max and min values of $s_i(t)$ at decision moment t for all station i,
- max_i, min_i $d_{vi}(t)$: the max and min values of $d_{vi}(t)$ at decision moment t for all station i,
- s_i : the normalized value of $s_i(t)$ ($0 \le s_i \le 1$),
- d_{vi} : the normalized value of $d_{vi}(t)$ ($0 \le d_{vi} \le 1$),
- α, β: weights of the vehicle empty travel distance and the net-stock respectively ($\alpha + \beta = 1$). Since the travel distance and the net-stock seem to be equally importance, weights of these factors should not be significantly different. Good

values for α and β are obtained from simulation experiments. In our experiments (0.5, 0.5) is a good set of values for (α, β).

Minimizing the vehicle empty travel distance (time) practically is an efficient approach to improve the system throughput. Therefore, we select the travel distance as one decision factor. As indicated before, balancing the system workload is important criterion for AGVSmV. An obvious way to do it is balancing vehicle requirements of all stations, so we also include this factor in the decision function.

The framework of the Multi-Att rule

- At a decision point (DC_i), a vehicle chooses the destination station based on the value of the decision function $f_{vi}(d,s)$ at the decision moment. The station with the smallest value of $f_{vi}(d,s)$ will be selected.
- If on the way to the destination station, the assigned vehicle passes another decision point (DC_j), this vehicle will be reassigned based on new values of the decision function at DC_j ($f_{vj}(d,s)$).

(d) The modified multi-attribute dispatching rule (Multi-Mod)

We modify the dispatching function of the Multi-Att rule to obtain a new dispatching rule - the modified multi-attribute dispatching rule (Multi-Mod). The dispatching function is described as follows:

$$f_{vi}\left(d,s\right)=\alpha\times d_{vi}+\beta\times\left(s_i\right)^{\gamma}$$

- γ: power coefficient obtained by experiments ($\gamma = 4$ is a good value in our experiments).
- Other parameters are the same as for Mutli-Att.

4 Experimental environments

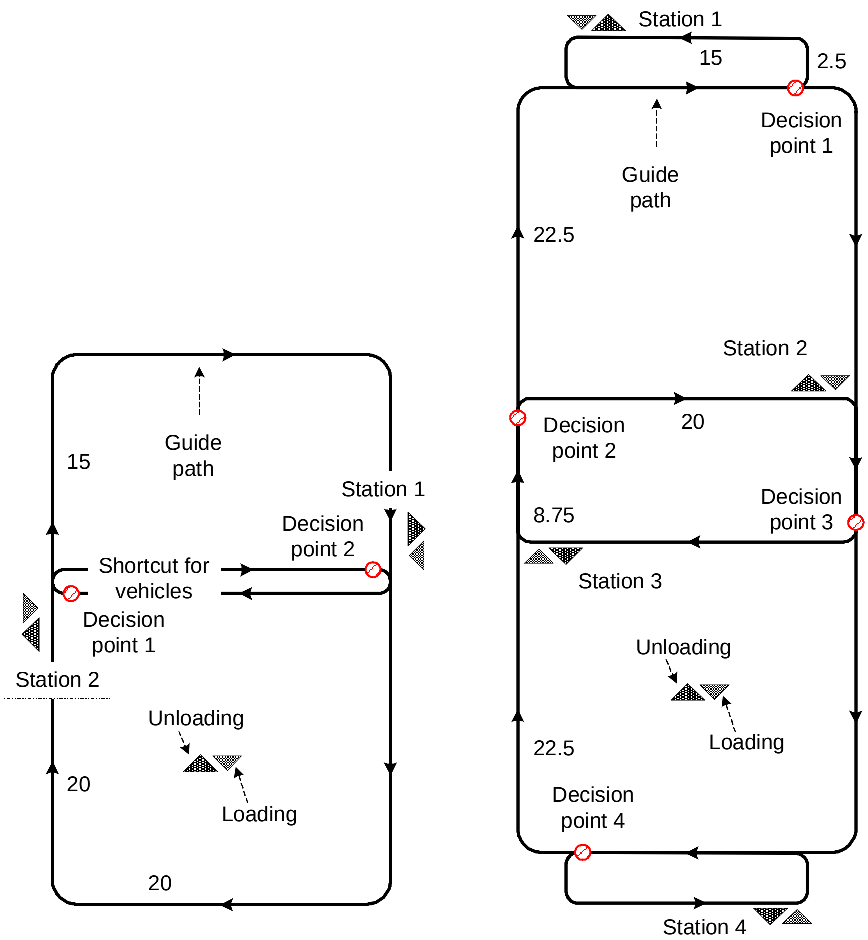

Figure 3 The experimental AGVSmV (2 stations - left and 4 stations - right)

In this study, we have selected two layouts for AGVSmV (adapted from Talbot (2003)), these layouts can be considered as simple cases of BHS systems. One layout contains two stations and another contains four stations with transportation requirements. The load arrival rates at each station can be different. When all load arrival rates at stations are the same, we have a balanced system, otherwise the system is unbalanced. We model these AGVSmV in AutoMod 10 simulation software. In our model, vehicles cannot run through each other.

In the simulation models, several assumptions are made:

- Vehicles operate continuously without any breakdowns,
- All vehicles have single-load capacity ,
- Vehicles choose the shortest path to pickup and deliver loads,
- Loads are generated in batches of one,
- There is no operational time lost due to recharging vehicles ,

- There is sufficient space for waiting loads.

Environment characteristics and experimental factors

Figure 3 represents the layout and travel times (in seconds) in two experimental AGVSmV. In the two stations layout, each station has one internal storage position for free (idle) vehicles and in the four stations layout each station has two internal storage positions for free (idle) vehicles. Vehicles do not have other parking locations in the system. Idle-vehicles have to travel a loop (main loop - the loop that does not cover any station). The loading and unloading time of a vehicle is 2.5 and 0 seconds, respectively.

Load arrival rates

Two stations case

- The load inter-arrival distribution at two stations is exponential and the load inter-arrival times (τ) at station 1 and station 2 are 3.5 seconds and 5 second respectively,
- The probabilities that a load is sent from a station *i* to a station *j* are p_{ij} (p_{11} = 0, p_{12} = 1, p_{21} = 1, p_{22} = 0).

Four stations case

Two load arrival scenarios are selected:

- Balanced case: load inter-arrival time at a station is exponentially distributed with inter-arrival times (τ_1, τ_2, τ_3, τ_4) = (12.2, 12.2, 12.2, 12.2) seconds.
- Unbalanced case: load inter-arrival time at a station is exponentially distributed with inter-arrival times (τ_1, τ_2, τ_3, τ_4) = (4.5, 6, 9, 18) seconds.
- For both scenarios, the probabilities that a load is sent from a station *i* to a station *j* are p_{ij} (p_{ii} = 0 for all *i*, p_{ij} = 1/3 for all *i, j* and $i \neq j$).

The number of vehicles

- Two stations case: 3 levels have been used (60, 65, 70).
- Four stations case: 3 levels have been used (70, 85, 100),

Vehicle dispatching rules

Four vehicle dispatching rules (STDF, EC, Multi-Att and Multi-Mod) are implemented. Threshold values for *EC* are (S_1 = 26, S_2 = 20) for the two stations case and are ($S_i = 7$, $\forall i$ = 1..4) and (S_1 = 10, S_2 = 8, S_3 = 6, S_4 = 4) for the four stations case (balanced and unbalanced scenarios) (adapted from Talbot (2003)). The parameters for the Multi-Att and Multi-Mod rules are (α, β) = (0.5, 0.5) and γ = 4 for all scenarios.

Performance criteria

The main performance criterion is minimizing the average load waiting time. The secondary objectives are minimizing the maximum load waiting time and the maximum number of loads in queues.

Simulation runs

For each scenario, a replication of ten runs of 120 minutes has been used to gather statistical information of performance indicators.

Statistical Analysis

The replication/deletion approach (see Law and Kelton, 1991) is used to determine values of performance indicators. Tukey's tests with 95% confidence interval (95%CI) are used to rank dispatching rules statistically under various experimental conditions.

5 Performance evaluation

5.1 The two stations case

The performance of Multi_Mod is the same as that of Multi_Att in this case, so we select only the Multi_Att rule for evaluation.

Table 1 Results for the two stations case

Perfor.	60 vehicles			65 vehicles			70 vehicles		
measure	*STDF*	*MultiA*	*EC*	*STDF*	*MultiA*	*EC*	*STDF*	*MultiA*	*EC*
Avewait	9.66	6.90	6.76	9.46	6.62	6.46	8.55	6.25	6.45
Maxwait	48.68	37.72	39.51	49.22	36.51	37.35	47.74	35.90	33.30
Max_Q	19	15	15	19	14	15	18	14	13

MultiA: multi-attribute dispatching rule (Multi_Att); *Avewait*, *Maxwait*: average and maximum load waiting times; *Max_Q*: the maximum number of loads in queues.

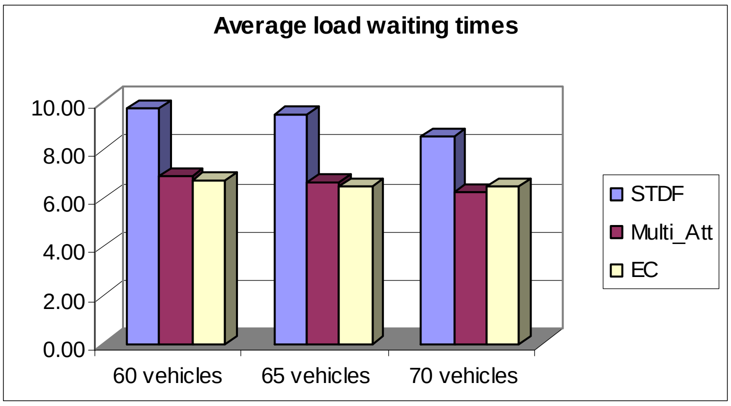

Figure 4 The average load waiting times for three rules

Table 1 and Figure 4 show that two dispatching rules (Multi_Att and EC) perform similarly. These two rules outperform the STDF rule for all three vehicles levels. These observations apply to all three performance criteria.

Table 2 The ranking of dispatching rules for the two stations case (Tukey's test 95%CI)

Rules	*60, 65, 70 vehicles*	
Multi-Att	1	
EC	1	
STDF		3

Table 2 indicates that the average load waiting times resulting of two dispatching rules (Multi_Att and EC) are about the same. The difference is not significant according to Tukey's test with 95% confidence level.

5.2 The four stations case

Table 3 Results for the four stations case

Scen.	Perfor. measure	70 vehicles				85 vehicles				100 vehicles			
		STDF	*MultiA*	*MultiM*	*EC*	*STDF*	*MultiA*	*MultiM*	*EC*	*STDF*	*MultiA*	*MultiM*	*EC*
Bala.	*Avewait*	9.61	6.09	5.35	5.46	6.88	2.95	2.60	2.67	5.50	2.09	1.94	2.23
	Maxwait	81.60	68.50	65.30	77.10	68.80	38.00	36.10	32.10	62.40	27.50	25.00	26.70
	Max_Q	14	11	12	12	12	8	7	8	12	7	7	7
Unba.	*Avewait*	52.80	23.51	35.97	190.5	11.00	6.95	7.92	7.14	8.13	3.55	3.28	3.02
	Maxwait	271.4	123.5	176.0	1073	88.80	65.30	72.90	79.20	70.10	40.90	47.10	32.90
	Max_Q	65	31	41	247	23	19	20	22	19	13	14	12

MultiA, *MultiM:* multi-attribute and modified multi-attribute dispatching rules (Multi_Att, Multi_Mod); *Scen*.: scenario; *Bala*., *Unba*.: balanced and unbalanced scenarios; *Avewait*, *Maxwait*: average and maximum load waiting times; *Max_Q*: the maximum number of loads in queues.

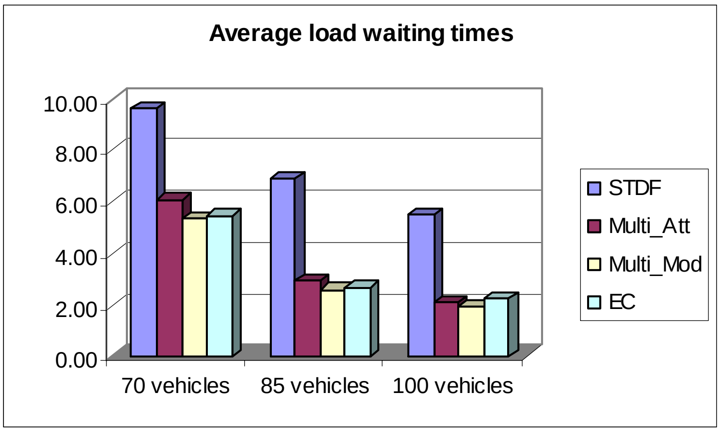

Figure 5 The average waiting times for four rules (the balanced scenario)

From Table 3, Figure 5 and Figure 6, we find that the STDF rule is still the worst rule in the four stations case. However, the ranking for the other three dispatching rules can be different when different numbers of vehicles are used. In the balanced scenario, the Multi_Mod rule performs a bit better than Multi_Att and EC. The average waiting times obtaining by three dispatching rules, are not significant different when 70 and 85 vehicles are used (Table 4). However, when we have more vehicles in the system (100) two dispatching rules (Multi_Att and Multi_Mod) perform significantly better than EC (Table 4).

Table 4 The ranking of dispatching rules for the four stations case, the balanced scenario (Tukey's test 95%CI)

Rules	*70, 85 vehicles*		*Rules*	*100 vehicles*		
Multi-Mod	1		**Multi-Mod**	1		
EC	1		**Multi-Att**	1		
Multi-Att	1		**EC**		3	
STDF		4	**STDF**			4

In the unbalanced scenario, when we have only 70 vehicles in the system, the EC rule performs worse than STDF. The two multi-attribute dispatching rules (Multi_Att and Multi_Mod) prove to be robust to different operating conditions. We should also take into account a fact that the parameters of Multi_Att and Multi_Mod are kept the same for all scenarios.

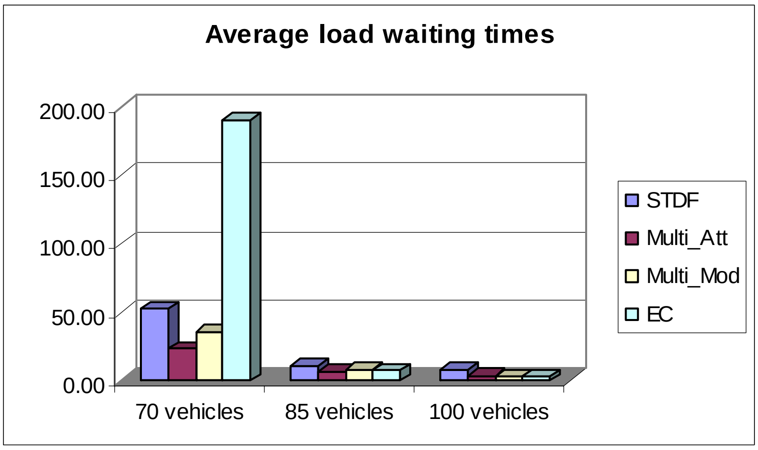

Figure 6 The average waiting times for four rules (the unbalanced scenario)

When higher numbers of vehicles (85, 100) are available in the system, the EC rule performs also well and about as well as two multi-attribute rules. This rule (EC) performs a bit better than two multi-attribute rules when 100 vehicles are used, but the differences are not significant (Table 5).

Table 5 The ranking of dispatching rules for the four stations case, the unbalanced scenario (Tukey's test 95%CI)

Rules	*70 vehicles*			*Rules*	*85, 100 vehicles*	
Multi-Att	1			**Multi-Att**	1	
Multi-Mod	1			**EC**	1	
STDF		3		**Multi-Mod**	1	
EC			4	**STDF**		4

According to Table 5, we can consider two multi-attribute dispatching rules (Multi_Att and Multi_Mod) as two best rules for the unbalanced scenario under various working conditions.

In general, we have found that the STDF works for AGVSmV, however, this rule performs not so well. The STDF dispatching rule which solely bases on travel distance to dispatch vehicle, may result in some stations having too many vehicles whereas other stations might be forgotten. This effect increases the average and maximum load waiting times. Two multi-attribute dispatching rules take into account the vehicle requirements at stations as well, so they can avoid this shortcoming of STDF. In our experiments, the two multi-attribute rules (Multi_Att and Multi_Mod) perform well under various working conditions and they perform similarly. Multi_Att performs better under the unbalanced condition (and with small numbers of vehicles). An explanation is that the net-stock of vehicles, which is responsible for balancing vehicle requirement among stations, has more influence on Multi_Att than on Multi_Mod. Multi_Mod performs a bit better than Multi_Att under the balanced scenario, however the difference is not significant.

The EC rule is similar to a type of decentralized dispatching rule. However, EC is not a decentralized dispatching rule, since this rule still requires some global system information such as the number of vehicles (loaded or empty) traveling on the link between the decision point *i* and station *i*, at the decision moment. The EC rule considers only information at one specific station at a decision moment, so it might cause unbalanced system workloads. This is the reason why the EC rule may perform badly under the unbalanced working condition. Multi_Att and Multi_Mod instead consider all stations at a decision moment.

6 Conclusions and further research

In this research, we have proposed two new multi-attribute dispatching rules (Multi-Att and Multi_Mod) which perform well and consistent for the two experimental AGVSmV. These dispatching rules are robust for different working conditions. Using simulation, we find that STDF, one of the best dispatching rules in literature performs not so well for AGVSmV. Talbot's (2003) EC dispatching rule performs well for AGVSmV, however the EC rule is not robust under various working conditions, particularly under unbalanced situations. Another disadvantage of the EC rule is that this rule requires threshold values (S_i) to operate and these values should be adapted dynamically for different working conditions. This makes the EC more difficult to implement in practice. Multi-Att and Multi_Mod perform well with a unique set of parameters. This makes Multi-Att and Multi_Mod rules more attractive from practical point of view.

Suggestions for further research

For future research, the main challenge is how to estimate the multi-attribute dispatching rules' parameters in a more systematic way. In addition, fuzzy logic might be used to improve the performance of the multi-attribute dispatching rules. If travel distances are significantly long, it might be more useful to setup some additional distributed parking locations for idle-vehicle in the system. However in this case, the guide-path system and dispatching policies have to be adapted accordingly.

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