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ONLINE DISPATCHING RULES FOR VEHICLE-BASED INTERNAL TRANSPORT SYSTEMS

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Abstract

On-line vehicles dispatching rules are widely used in many facilities such as warehouses to control vehicles' movements. Single-attribute dispatching rules, which dispatch vehicles based on only one parameter, are used commonly. However, multi-attribute dispatching rules prove to be better in general. In this study, we introduce new dispatching rules and evaluate their performance compared to several good dispatching rules in literature, using the experimental design of a real case study. The performance criteria are minimizing the average load waiting time while keeping the maximum load waiting time as small as possible and better utilize vehicles. The experiments show that newly introduced hybrid dispatching rule yields the best performance overall.

Keywords: On-line dispatching, vehicle-based internal transport system, centralized control, performance.

1 Introduction

In environments such as warehouses, distributions centres and production facilities guided vehicles are important means to transport loads between internal storage locations (or workstations in a manufacturing facility). Modern guided vehicles travel under control of a shop floor control system without human interferences. Such vehicles are referred to as automated guided vehicles (AGVs). The performance of internal transport systems using automated guided vehicles depends on several factors such as the guide-path layout and the vehicle scheduling system (see Le-Anh and De Koster, 2003). In internal transport environments, exact information about load arrivals is usually only known a little moment in advance. Due to this problem, scheduling vehicles in these systems in advance is nearly impossible. The best solution is to use on-line dispatching rules to control vehicles.

Vehicle dispatching rules are usually simple and easy to use. A vehicle control system using a dispatching rule, controls vehicles' movements based on some intuitive reasoning aiming at a good system performance. In literature, much effort is put into improving the performance of vehicle dispatching rules. A best rule for all cases does not exist; however we can find good rules for specific cases. Among single-attribute dispatching rules, the distance-based dispatching rules such as the nearest-workstation-first rule (NWF) tend to have a good performance (Van der Meer and De Koster, 2000). Several researchers have developed multi-attribute dispatching rules in a search for better vehicle dispatching rules (Klein and Kim, 1996; Hwang and Kim, 1998; Jeong and Randhawa, 2001).

In this paper, we contribute to the development of vehicle dispatching rules by proposing new dispatching rules that are quite simple, efficient and easy to implement in practice. We also evaluate the performance of several well-performing dispatching rules, from literature and new dispatching rules under various operating conditions using an experimental design of a real case study.

This paper is organized as follows: section 2 studies the literature on on-line dispatching; section 3 describes dispatching rules used in this paper; section 4 illustrates the case study and experimental setup; section 5 provides a performance evaluation of dispatching rules and conclusions are given in section 6.

2 Literature survey

On-line dispatching systems can be divided into two main categories: decentralized and centralized control systems (Van der Meer, 2000). The decentralized system dispatches vehicles based on only local information available at the decision moment. The centralized control 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 dispatching systems are more popular. Depending on the ways in which transportation requests are assigned, dispatching rules can be divided into two categories (Egbelu and Tanchoco, 1984): 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 rule. 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 pick up, using a vehicle-initiated rule. Therefore load-initiated dispatching rules described by Egbelu and Tanchoco (1984) are actually a combination of load- and vehicle-initiated rules in which loads have priority to claim vehicles.

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 for itself. A load in the system using vehicle-initiated dispatching rules cannot claim a vehicle but they can wake a vehicle upon arrival and then this vehicle will search for a load to pick up.

Dispatching rules can also be classified into single-, multi-attribute and hybrid dispatching rules. Single-attribute dispatching rules dispatch vehicles based on only one parameter such as the vehicle empty travel time. Multi-attribute dispatching rules dispatch vehicles based on a multi-attribute dispatching function and hybrid dispatching rules consider several types of vehicle assignments at the same time.

Most dispatching rules in literature are single-attribute dispatching rules. Some common single-attribute dispatching rules in literature are the shortest-travel-distance-first (STDF), the first-come-first-served (FCFS), the modified-first-come-first-served (MODFCFS), the maximum-outgoing-queue-size (MOQS) and the 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, the distance-based dispatching rules such as STDF tend to have a good performance in general, particularly where queues' capacities are not restriction.

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. The 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. They show that multi-attribute dispatching rules are superior to single-attribute dispatching rules. In their experiments, among single-attribute dispatching rules, the STDF rule provides the best performance and can be comparable to multi-attribute dispatching rules according to several criteria. However, the STDF rule is sensitive to the guide-path layout (as far away low-density areas may be neglected), so multi-attribute dispatching rules have a better performance in general. 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. In their research, an additive waiting model was used to compute weights for member parameters. A neural network was used to dynamically adjust the parameters' weights reflecting changes in the system. According to their results, 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 find that, in general, multi-attribute dispatching rules provide a better performance than single-attribute dispatching rules.

Bozer and Yen (1996) propose two hybrid dispatching rules: modified-shortest-distance-time-first (MODSTDF) and bidding-based device dispatching (B^2D^2). Under MODSTDF, a vehicle moving to a parking location or traveling to pick-up a load can be reassigned to pick-up a load at another location. These rules outperform STDF in their experiment environments. However, these two rules still have the same drawback as the shortest-travel-time-first rule: they are sensitive to the system guide-path layout.

Van der Meer and De Koster (2000) evaluate the performance of several single-attribute dispatching rules for a real case study. In this paper, we extend their research by testing the performance of single-, multi-attribute and also hybrid dispatching rules in practice, including several new dispatching rules. Using simulation, we will show that the new hybrid dispatching rule (*Hybrid*) provide the best performance overall and we also prove that the multi-attribute and hybrid dispatching rules outperform single-attribute dispatching rules in practice.

3 Dispatching rules

In this paper, we select two most commonly used single-attribute dispatching rules (NWF, MODFCFS), some variations of multi-attribute dispatching rules and a hybrid rule (MODSTDF) for evaluation. These dispatching have a very good performance as in indicated in the literature. We also propose three new dispatching rules (*Multi-mod, NVF_R and Hybrid*). Characteristics of dispatching rules used in this paper are provided in Table 1. For all rules in Table 1, when a vehicle becomes idle (and has not been claimed by a load) and cannot find any load in the system for transportation, this vehicle will park at the closest parking location.

Table 1 Dispatching rules and their characteristics

	Vehicle-initiated	*Workstation-initiated*	*Time priority*	*Reassign-ment*	*Cancella-tion*	*Sources*
Single-attribute dispatching rules						
MODFCFS	✓					Srinivasan et al. (1994)
NWF	✓					Egbelu and Tanchoco (1984)
Multi-attribute dispatching rules						
Multi-att	✓		✓			Klein and Kim (1996)
Multi-mod	✓		✓			This paper
Hybrid dispatching rules						
NVF_R	✓	✓		✓		This paper
Hybrid	✓	✓	✓	✓		This paper
NVF_RC	✓	✓		✓	✓	Similar to MODSTDF Bozer and Yen (1996)

3.1 Single-attribute dispatching rules

(a) Modified First-Come-First-Served (MODFCFS)

A vehicle operating under MODFCFS, introduced by Srinivasan *et al*. (1994), delivering a load at the input queue of station *i*, first inspects the output queue of that station. The vehicle is then assigned to the oldest request (longest waiting load) at station i if one or more loads are found. However, if the output queue of station i is empty, the vehicle serves the oldest request in the entire system.

(b) Nearest Workstation First (NWF)

In this case, a released or idle vehicle searches for the closest available load to pickup. The closeness is measured in terms of travel distance. Sometimes however, a facility layout may contain a few remote stations. The stations not near a vehicle release point can therefore hardly qualify to receive a vehicle dispatch. This illustrates the major drawback of this rule; it is sensitive to the layout of the facilities.

3.2 Multi-attribute dispatching rules

(a) Multi-attribute dispatching rule (Multi-att)

In the case study (a distribution center), capacities of queues are not the bottleneck in the system, so mainly vehicle travel distances and load waiting times affect the system performance. Therefore we choose vehicle empty travel distance and load waiting time to be decision attributes. Let dis_{vi} denote the empty travel distance from the current vehicle (v) location to the pickup location i and $wait_{vi}$ denote the waiting time of load i. dis_{vi} and $wait_{vi}$ are normalized to DIS_{vi} and $WAIT_{vi}$ using the following expressions:

$$DIS_{vi} = \frac{dis_{vi} - \min_j dis_{vj}}{\max_j dis_{vj} - \min_j dis_{vj}} \; ; \; WAIT_{vi} = \frac{\max_j wait_{vj} - wait_{vi}}{\max_j wait_{vj} - \min_j wait_{vj}}$$

The attributes DIS_{vi} and $WAIT_{vi}$ are used to compute the score function S_{vi}.

$$S_{vi} = w_1 \times DIS_{vi} + w_2 \times WAIT_{vi} \; ; \; w_1 + w_2 = 1$$

w_1, w_2 are weights of the vehicle empty travel distance and the load waiting time respectively.

The score function S_{vi} is then used to select the suitable load for a vehicle. When a vehicle becomes idle, this vehicle searches for a load to pickup as follows:

- If the vehicle finds one or more transportation requests in the system then:
  - Values of the score function for all waiting loads in the system are calculated,
  - A load that has the smallest value of the score function is chosen to be picked up,
- If the vehicle cannot find a job, it goes to the closets parking location and remains idle until being awakened by a load or by another vehicle.

Results of Jeong and Randhawa (2001) reveal that the additive multi-attribute rule performs better with a higher weight of the unloaded (or empty) vehicle travel distance. In addition, results of Van der Meer and De Koster (2000) show that distance-based dispatching rules perform better than time-based dispatching rules, so we give a higher weight to the vehicle empty travel distance attribute. Depending on the specific case, the best attribute weights can be found by experiments. In this case we select the weights of travel distance and waiting time to be 0.8 and 0.2 respectively.

(b) Modified multi-attribute dispatching rule (Multi-mod)

To investigate the influence of load waiting time on multi-attribute dispatching function further, we adopt a new modified multi-attribute dispatching rule with a score function (Sn_{vi}) as follows:

$$Sn_{vi} = w_1 \times DIS_{vi} + w_2 \times \left(WAIT_{vi}\right)^p ;\; w_1 + w_2 = 1 ;$$

where p is an integer greater than one and is chosen to be three in this case. Weights of travel distance and waiting time are determined in the same manner as for the multi-attribute dispatching rule and are also 0.8 and 0.2 respectively. According to the score function Sn_{vi}, the waiting times have less influence then in the score function S_{vi}.

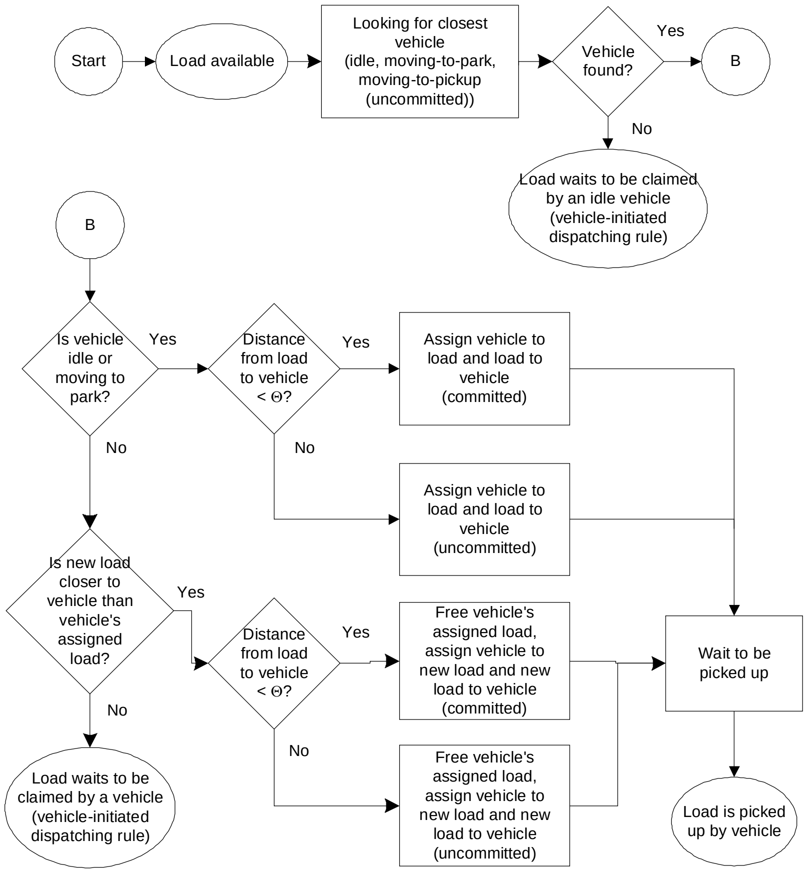
3.3 Hybrid dispatching rules

(a) Nearest Vehicle First with vehicle Re-assignment (NVF_R)

This rule is a load-initiated dispatching rule and is similar to NWF. The difference is that when a load enters the system, this load can immediately search for available vehicles. If idle or moving-to-park vehicles are found, this load claims the nearest vehicle to carry it out. Otherwise this load waits on the system load waiting list until an idle vehicle claims it. When a vehicle becomes idle and is currently not claimed by any load, this vehicle searches for the closest load in the system (vehicle-initiated).

(b) Nearest Vehicle First with vehicle Re-assignment and Cancellation (NVF_RC)

This rule is similar to the MOD STTF of Bozer and Yen (1996). MODSTTF is a load-initiated dispatching rule. When a load just enters the system, this load immediately searches for a vehicle as indicate in Figure 1. If this load can not find any vehicle, it waits on the system load waiting list until being claimed by an idle vehicle.



*(Vehicle status: **idle**: vehicle stay idle (has no job) at a parking location; **moving-to-park**: a vehicle has no job and is traveling to a parking location; **moving-to-pickup**: a vehicle is traveling to the vehicle's assigned load pickup location; **committed**: means that the vehicle cannot be diverted to another destination, **uncommitted** otherwise.)*

Figure 1 The impact of the load behavior on dispatching rules with vehicle reassignment.

When a vehicle is travelling-to-pickup a load, a new just arriving load can claim this vehicle only if the load that this vehicle is going to pick up, is not committed to this vehicle. A load is committed to a vehicle if the vehicle claims the load and the travel distance from the vehicle to the load is smaller than a distance threshold Θ (chosen around the value of the average load transportation time). When a vehicle becomes idle, this vehicle searches for a load as described in Figure 2.

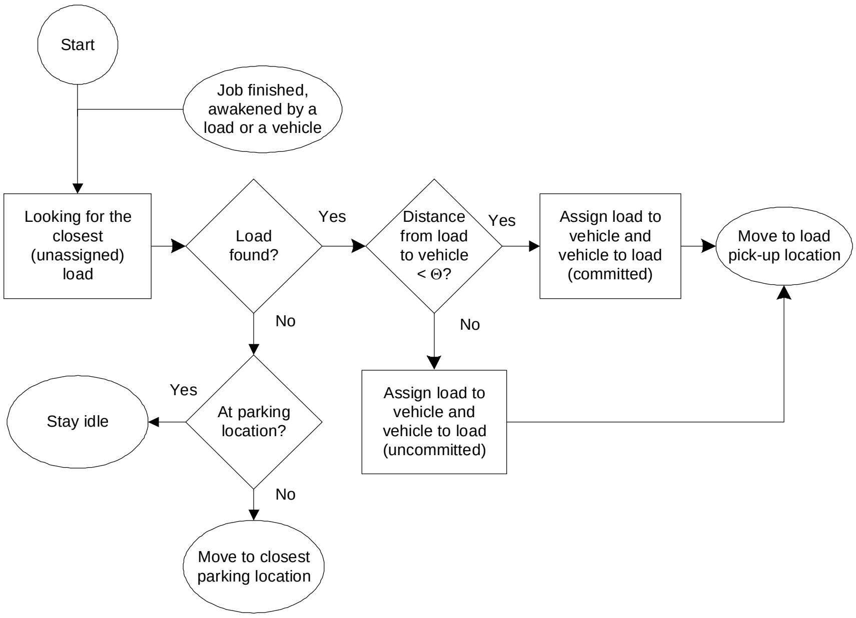


Figure 2 Vehicle-initiated dispatching.

(c) Hybrid dispatching rule (Hybrid)

It is possible to improve multi-attribute dispatching rules by applying vehicle reassignment. Hence, we introduce a new rule (*Hybrid*), which uses vehicle reassignment in combination with multi-attribute dispatching. This rule is a load-initiated dispatching rule. When a load just enters the system, this load checks for an available vehicle (idle or moving-to-park). We do not use cancellation here (reassigning moving-to-pick-up vehicles) since cancellation may eliminate the effect of multi-attribute dispatching. If this load can find one, it claims that vehicle, and the vehicle is redirected to pickup the load. Otherwise this load waits on the system load waiting list to be claimed by an idle vehicle. An idle vehicle selects a load to transport using the score function similar to the multi-attribute dispatching rule (*Multi-att*).

4 Experimental set-up

4.1 The case study

The case study concerns the transportation of pallet loads at the European distribution center of a computer hardware and software wholesaler. Because computer products change quickly over time, it is necessary to keep inventory levels low and the storage times as short as possible. Five forklifts with vehicle-mounted terminals are used to transport the pallets.

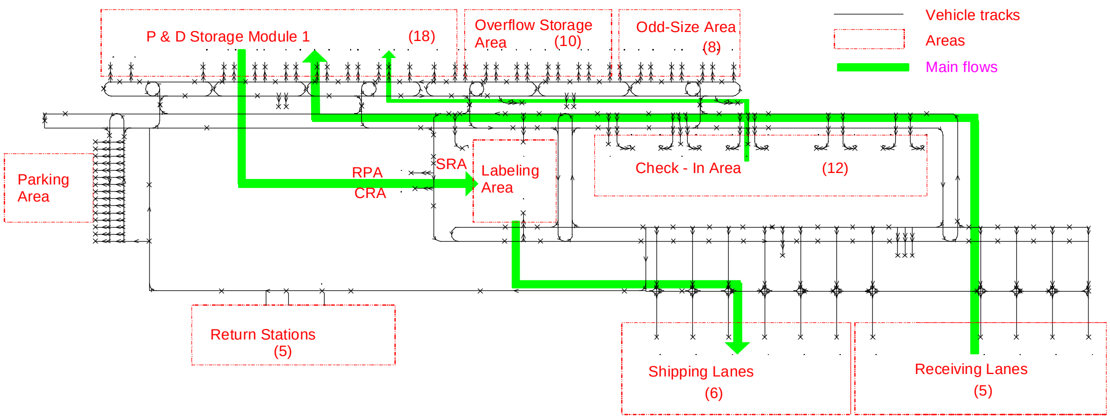


Figure 3 Guide-path layout of the EDC (four main pallet flows are indicated)

The distribution center can be divided into several areas (see Figure 3). Each weekday, trucks arrive at the *Receiving Lanes* of the distribution center where the pallets (loads) are unloaded. From there, loads are either first palletized at the check-in stations, or they are transported to the storage areas (although often intermediate stations, such as return stations, CRA or RPA). At each of the intermediate stations, loads are restacked on pallets that need to be stored. From the storage areas there are main flows to the shipping lanes (other via intermediate stations, such as the labeling area). The main flows are indicated in Figure 3. Van der Meer and De Koster (1998) describe the flows in more detail.

Simulation Environment

Relevant aspects of the warehouse and GVs have been modeled in the AutoMod simulation software package (version 8.2). The data on load release times, origins and destinations come directly from the database of the WMS of the company. Other parameters such as vehicle speed, pickup times come from careful measurements made at the distribution center. All the parameters (except experiment factors) are kept the same for each dispatching scenario. Table 2 gives a summary of some parameters for the basic scenario of the simulation model.

Table 2 The parameters used for a basic scenario (currently used in practice)

GV speed	2 m/s
Pick up time of a load	15 s
Set down time of a load	15 s
Load generated per hour	77
Vehicle capacity	1 load (pallet)
Number of vehicles	5
Number of working hours per day	7.5 hours

The load release times and release locations have been measured for a period of six weeks. The requests for a certain transport depend highly on the time of day and can be modeled properly by Poisson distributions (this has been tested using a series of χ^2-tests). Each type of transport is independently exponentially generated at its own rate. Each day is in turn divided into four periods to realistically represent the variation in the inter-arrival rates over the day. The variation in pick-up and drop-off time of loads is very small so we consider these to be deterministic.

4.2 Experimental environment and factors

In the simulation model, 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

The replication/deletion approach (see Law and Kelton, 1991) is used to determine values of performance indicators. For each combination of experimental factors, a replication of ten runs is used to determine results. Analysis-of-variance (ANOVA) technique is used to analyse the interaction between experimental factors. In addition, Tukey tests (using SPSS - Marija, 2000) are used to rank dispatching rules statistically on different performance criteria and under various experimental conditions.

The main performance criterion in this case study is minimizing the average load waiting time. We also take into consideration the maximum load waiting time and the vehicle utilization. Four experimental factors are considered. They are dispatching rule (7 levels), load generation rate (3 levels), load generation distribution (2 levels), and load pickup/drop-off time (2 levels). Therefore we have a 7×3×2×2 full factorial experiment. The dispatching rules are described in section 3. These experimental factors were selected since they have big influences on the system performance. Other experimental factors such as vehicle speed are related to above four factors, so we limit the number of basic experimental factors to four.

Load generation rate

We experiment with three levels of the load generation rate (low (-25%), medium, high (+25%)). The medium rate is the current load arrival rate at the distribution center. The other two rates are generated to test if different dispatching rules have similar behavior under different levels of load arrival rates (and also different levels of the vehicle utilization).

Load generation distribution

The load arrival distributions in this case follow Poisson distributions. However, we want to check the behavior of dispatching rules when another distribution type is used. Therefore, the gamma distribution with shape parameter (α = 2) is used to generate load inter-arrival times. With this parameter, it has the same mean, but has a smaller variance than the exponential distribution.

Load pickup/drop-off time

We distinguish two levels of load pickup and drop-off times for loading and unloading parts (loads) at a workstation: low (the time needed to pickup/ drop-off a load currently), and high (the current required time plus 30%) are implemented.

5 Performance evaluation

Results are summarized in experimental results tables (Table 3, Table 4, Table 5, Table 6). Figure 4, Figure 5 and Figure 6 provide the ranking of dispatching rules in different operating conditions based on Tukey tests (95% confidence level). In some cases, overlaps between ranking groups exist, however, we show only dominating ranking groups for a clearer reference. In the performance evaluation, if rules have a similar performance on minimizing average and maximum load waiting times, we prefer rules yielding lower vehicle utilization rates. A low vehicle utilization rate means that we can still try to operate the system with a smaller number of vehicles.

Table 3 ANOVA results

	Average waiting time		Max waiting time		Vehicle utilization	
	F	Sig.	F	Sig.	F	Sig.
LOADRATE	**13366.24**	**0.00**	**9890.15**	**0.00**	**346613.28**	**0.00**
DIST	**787.76**	**0.00**	**476.98**	**0.00**	6.73	0.02
PICKTIME	**1384.08**	**0.00**	**892.71**	**0.00**	**9855.21**	**0.00**

RULE	**1241.56**	**0.00**	**248.64**	**0.00**	**1111.55**	**0.00**
LOADRATE * DIST	**270.81**	**0.00**	**79.06**	**0.00**	**33.43**	**0.00**
LOADRATE * PICKTIME	**724.76**	**0.00**	**477.80**	**0.00**	**84.23**	**0.00**
LOADRATE * RULE	**747.76**	**0.00**	**173.70**	**0.00**	**161.94**	**0.00**
DIST * PICKTIME	**65.13**	**0.00**	**23.37**	**0.00**	3.71	0.08
DIST * RULE	5.97	0.01	1.94	0.16	**6.43**	**0.00**
PICKTIME * RULE	1.04	0.45	**10.64**	**0.00**	2.05	0.14
LOADRATE * DIST * PICKTIME	**36.75**	**0.00**	6.82	0.01	2.22	0.15
LOADRATE * DIST * RULE	2.65	0.06	2.24	0.10	2.04	0.12
LOADRATE * PICKTIME * RULE	0.83	0.62	**6.08**	**0.00**	0.31	0.97
DIST * PICKTIME * RULE	0.96	0.49	0.83	0.57	1.48	0.27

{**Factors:** *LOADRATE: load generation rate; DIST: load generation distribution; PICKTIME: pickup/drop-off time; RULE: dispatching rules.* **Bold numbers** *indicate that the effects are significant at 95% confidence level}*

The ANOVA table (Table 3) indicates that all experimental factors have significant effects on the system performance metrics. However, the load generation distribution seems to have a small effect on the vehicle utilization (Table 3). Considering two-way interaction of variables, two combinations (DIST * RULE and PICKTIME * RULE) have smaller influences on the system performance. The three-ways interaction analysis shows that the LOADRATE * DIST * PICKTIME combination has obvious effects on the average load waiting time and the standard deviation, and the LOADRATE * PICKTIME * RULE combination has a clear impact on the maximum load waiting time. Other three-way interactions are not significant.

5.1 Low load generation rate

Table 4 and Figure 4 show that dispatching rules using vehicle reassignment (NVF_RC, NVF_R and *Hybrid*) perform very well in this case, particularly in minimizing the average load waiting time. The vehicle utilizations of three rules using vehicle reassignment are significantly smaller than for the other four rules. NVF_RC is the best rule according to minimizing the average load waiting time criterion according to the Tukey test. The second best group is two reassignment rules (NVF_R and *Hybrid*). The MODFCFS rule is the worst rule concerning this performance criterion. However, a reverse order is obtained when we compare the maximum load waiting time of the system using these dispatching rules. The best rules in term of the average waiting time score poorly in term of the maximum load waiting time.

Table 4 Experimental results (low load generation rate)

Load gen.rate	Distri-bution	Pick time	Perf. metric	Dispatching rules						
				MODFCFS	**NWF**	**NVF_R**	**NVF_RC**	**Multi-att**	**Multi-mod**	**Hybrid**
Low	**Exponential**	**15**	**Avewait**	100.69	97.42	85.59	82.45	97.45	97.53	85.68
			maxwait	290.87	378.70	411.63	443.12	358.78	365.35	414.62
			util%	55.74	55.26	52.59	52.00	55.26	55.27	52.58
		20	**Avewait**	109.53	105.28	93.90	90.32	105.15	105.20	94.05
			maxwait	322.64	427.24	475.60	490.34	414.83	417.42	458.62
			util%	58.48	57.95	55.47	54.86	57.92	57.93	55.46
	Gamma	**15**	**Avewait**	92.91	91.61	76.97	74.92	91.66	91.63	77.03
			maxwait	232.70	261.43	334.40	348.09	256.25	252.23	331.87
			util%	55.51	55.27	51.77	51.32	55.28	55.28	51.77
		20	**Avewait**	99.99	97.87	84.02	81.67	98.00	97.96	84.08
			maxwait	259.21	292.23	350.74	354.72	285.94	289.05	338.78
			util%	58.28	57.98	54.66	54.17	58.00	58.00	54.67

{Load gen.rate: load generation rate; Distribution: load generation distribution; Pick time: pickup/drop-off time (s); Perf. metric: performance metric (criterion); Avewait: average load waiting time (s); maxwait: maximum load waiting time (s); util%: vehicle utilization (%)}

To evaluate the overall performance of rules we consider the relative importance of performance criteria. The most important criterion is minimizing the average waiting times. Hence rules, which perform better in terms of minimizing the average waiting time, have advantages. The vehicle utilization is in favor of dispatching rules using vehicle reassignment. The only disadvantage of the rules with vehicle reassignment is that they perform worse in terms of the maximum load waiting time. However, the largest load waiting time are still about only 8 minutes.

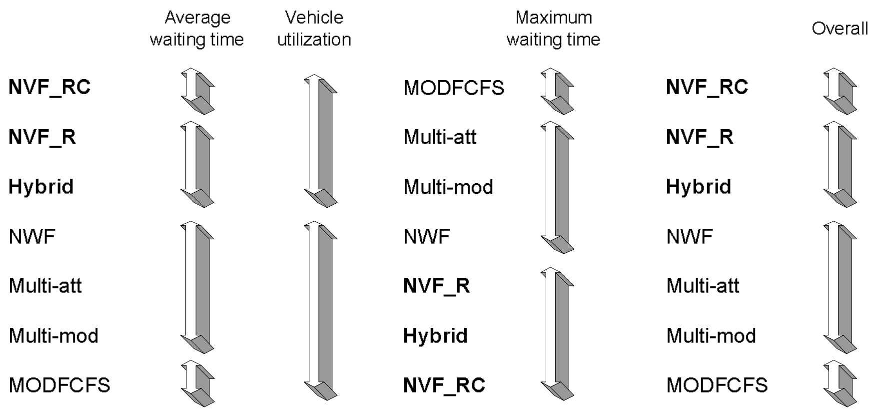


Figure 4 Rank of rules (low load generation rate)

In this case, vehicle utilization is around 55%. It means that vehicles have much idle time, so the problem that loads at remote areas might be neglected is unlikely. This explains why the highest value of max load waiting times is not high and around five times the corresponding average load waiting time. Therefore, in this case, the maximum waiting time ranking does not affect the overall ranking of dispatching rules (Figure 4).

5.2 Medium load generation rate

Under medium workload condition, we observe a similar result (Table 5 and Figure 5) as in the previous case. Three dispatching rules using vehicle reassignment belong to the same performance group considering minimizing the average waiting time criterion. Vehicles operating under reassignment rules have more idle time (lower vehicle utilization) than when they use other rules. The MODFCFS rule and multi-attribute dispatching rules (*Multi-att* and *Multi-mod*) are superior in terms of minimizing the maximum load waiting time. According to this performance metric MODFCFS is slightly better, but not significant.

Table 5 Experimental results (medium load generation rate)

Load gen.rate	Distri-bution	Pick time	Perf. metric	Dispatching rules						
				MODFCFS	**NWF**	**NVF_R**	**NVF_RC**	**Multi-att**	**Multi-mod**	**Hybrid**
Medium	**Exponential**	**15**	**Avewait**	182.46	134.19	125.99	119.81	135.43	133.53	127.96
			maxwait	704.01	1156.99	1154.44	1136.92	967.30	1039.45	866.53
			util%	79.00	76.43	74.77	73.23	76.46	76.43	74.76
		20	**Avewait**	244.88	158.76	155.68	144.56	157.93	158.11	154.18
			maxwait	1012.79	1540.66	1713.51	1560.89	1174.87	1366.77	1193.88
			util%	83.16	80.22	78.69	77.73	79.97	80.12	78.61
	Gamma	**15**	**Avewait**	143.20	113.82	105.55	96.99	113.13	113.34	105.40
			maxwait	497.85	738.74	714.32	748.79	558.63	637.05	578.29
			util%	79.19	77.15	74.92	73.14	77.11	77.08	74.89
		20	**Avewait**	181.88	129.98	122.92	114.21	131.02	129.50	123.30
			maxwait	673.44	988.95	1026.66	1008.23	744.08	846.86	692.18
			util%	83.10	80.65	78.91	76.99	80.73	80.72	78.73

In this case, the *Hybrid* rule is the best rules considering all performance criteria. This rule is in the best performance group of both average and maximum load waiting times and has good performance in other criteria. Figure 5 shows the rank of rules according to different criteria and the overall rank of rules.

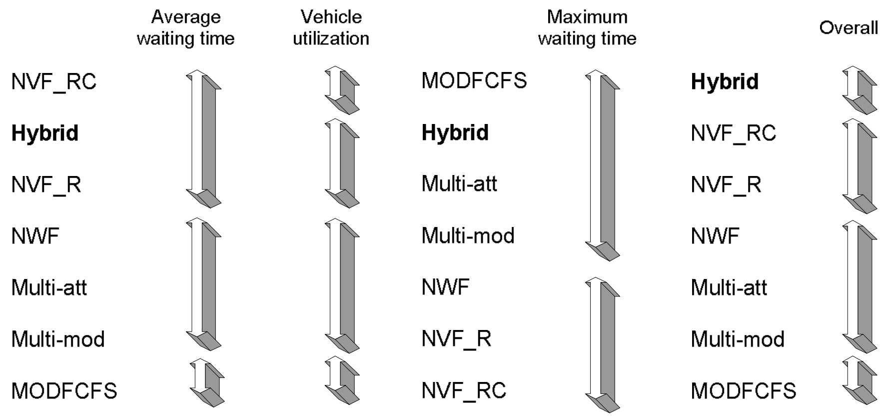


Figure 5 Rank of rules (medium load generation rate)

5.3 High load generation rate

Under a high workload condition, the performance of all rules, except MODFCFS, is quite similar considering the average and standard deviation of load waiting times. MODFCFS is the worst rule. It even becomes unstable in some cases, for example when the pickup/drop-off time is high. For this we need more vehicles to stabilize the system. Multi-attribute rules and the *Hybrid* rule are the best rules to minimize the maximum load waiting time.

Table 6 Experimental results (high load generation rate)

Load gen.rate	Distri-bution	Pick time	Perf. metric	Dispatching rules						
				MODFCFS	**NWF**	**NVF_R**	**NVF_RC**	**Multi-att**	**Multi-mod**	**Hybrid**
High	**Exponential**	**15**	**Avewait**	1066.93	277.80	273.51	283.22	279.54	273.34	282.75
			maxwait	4094.87	4088.86	3935.59	4224.52	2280.97	2969.64	2358.80
			util%	98.03	91.57	91.44	90.23	91.80	91.60	91.37
		20	**Avewait**	Not stable	484.88	449.61	473.79	443.06	454.43	453.00
			maxwait		6174.46	5894.70	6285.56	3372.35	4451.77	3384.92
			util%		95.57	95.15	95.29	95.64	95.59	94.81
	Gamma	**15**	**Avewait**	953.88	230.50	217.25	207.50	225.73	222.29	220.74
			maxwait	3529.09	3739.34	3603.66	3545.68	1893.50	2321.81	1785.03
			util%	98.39	92.04	91.28	89.67	92.14	92.06	91.25
		20	**Avewait**	Not stable	326.17	345.42	321.40	340.11	348.76	340.31
			maxwait		5093.81	5377.43	4867.17	2674.21	3669.98	2658.69
			util%		95.23	95.24	93.88	95.49	95.53	95.21

According to Table 6 and Figure 6, there is no the best rule, however, three rules (*Multi-att*, *Multi-mod* and *Hybrid*) can be considered as the better rules.

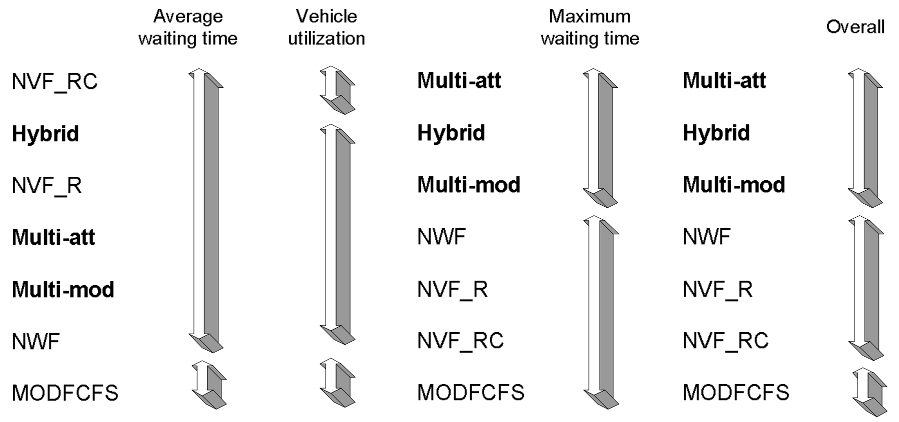


Figure 6 Rank of rules (high load generation rate)

5.4 Discussion

Table 4, Table 5 and Table 6 indicate that dispatching rules perform better under a gamma load generation distribution for all criteria. An explanation is that in this case the gamma distribution with a shape parameter α = 2, has a smaller variance compared with the exponential distribution (with the same mean value). High loading/unloading times reduce the performance of dispatching rules, since in this case the required time for a vehicle to serve a load increases.

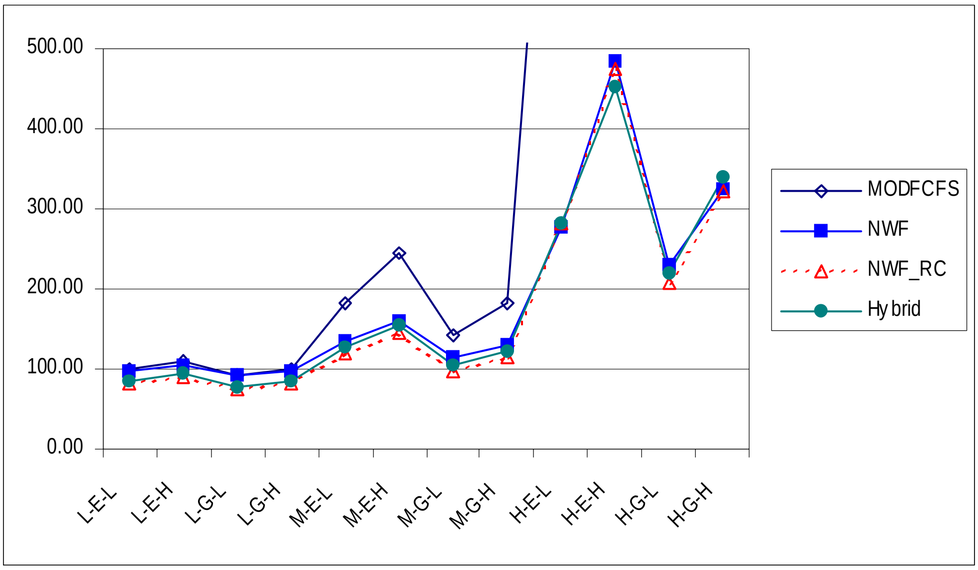


Figure 7 Average load waiting times

{Load generation rate [low - L, medium - M, high – H] - Load generation distribution [exponential - E, gamma – G] - Pickup/Drop-off time [low – L, high – H]}

Figure 7 and Figure 8 present graphs for the average and maximum waiting times of four dispatching rules under different operating conditions. In Figure 7, points depicting the average load waiting times in the system using NVF_RC and *Hybrid* are close to each other and lower than points representing the average load waiting times of others rules. The differences are higher in the low and medium load generation rate cases. This indicates that the NVF_RC and *Hybrid* rules perform much better than other rules with respect to the average waiting time.

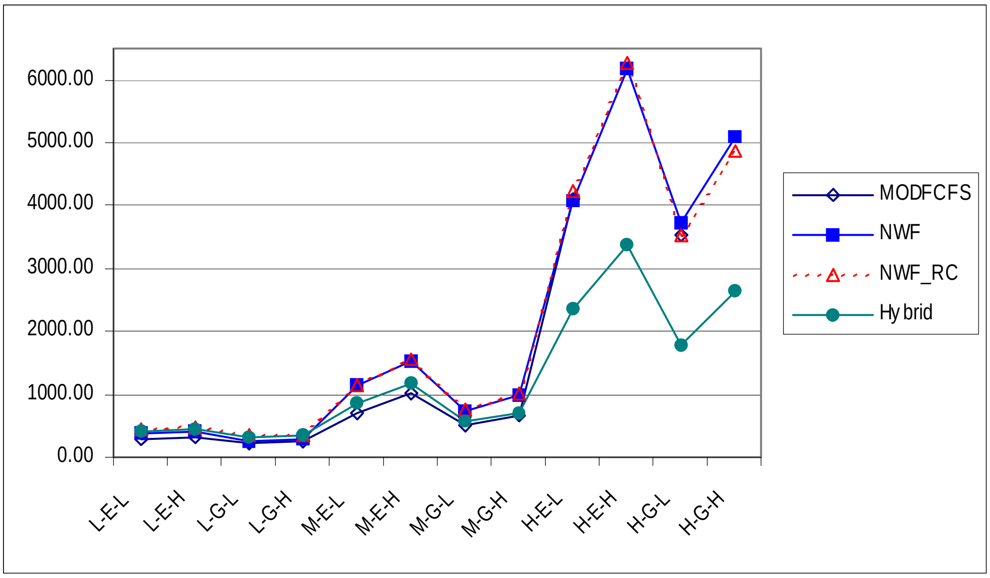


Figure 8 Maximum load waiting times

According to Figure 8, the MODFCFS rule provides the best value of the maximum load waiting time under light and medium workload conditions. However, under high workload condition, the *Hybrid* rule performs much better. Multi-attribute rules and the *Hybrid* rule perform similarly according to minimizing the max load waiting time criterion.

Operating under light workload condition, vehicles have more idle time. Therefore, there is a high chance that a vehicle is going to park when a load is available to be picked up, but the vehicle still has to go to park first. Reassigning a vehicle to pickup a load immediately at the time when it is available, will save unnecessary vehicle movements and increase the system performance. That explains why dispatching rules using vehicle reassignment perform very well under light workload condition. Under high workload condition, vehicles are busy most of the time, so reassigning vehicles does not have a big influence. Alternatively, multi-attribute dispatching rules, which also take the load waiting time or other parameters into account, gain a better performance considering all criteria.

6 Conclusions

In this paper, we propose three new dispatching rules to control vehicles' movements in internal transport systems. We also test the performance of the new rules and several dispatching rules in literature, which are reported to have a good performance (NVF_RC, *Multi-att*) or are widely used in practice (MODFCFS, NWF) under various operating conditions. The influences of experimental factors and interactions among them are discussed.

Results reveal that the dispatching rules using vehicle reassignments (NVF_RC, NVF_R and *Hybrid*) perform very well in minimizing the average load waiting time. On the other hand, MODFCFS, multi-attribute rules (*Multi-att* and *Multi-mod*) and the *Hybrid* rule perform very well to minimize the maximum load waiting time. According to experimental results, the *Multi-mod* rule gives about the same performance as the Multi-att rule, no improvement is observed. Impressively, the *Hybrid* rule has a very good performance concerning all criteria for different load generation rates and under different operating conditions.

NVF_RC rule performs well to minimize the average load waiting time, but has a worse performance in minimizing the maximum load waiting time. The MODFCFS rule performs quite well to minimize the maximum load waiting time, but is the worst rule if we consider minimizing the average waiting time as the main criterion. In general, the new *Hybrid* rule gives the best overall performance in all cases. Figure 9 shows the overall rank of the dispatching rules studied in this paper.

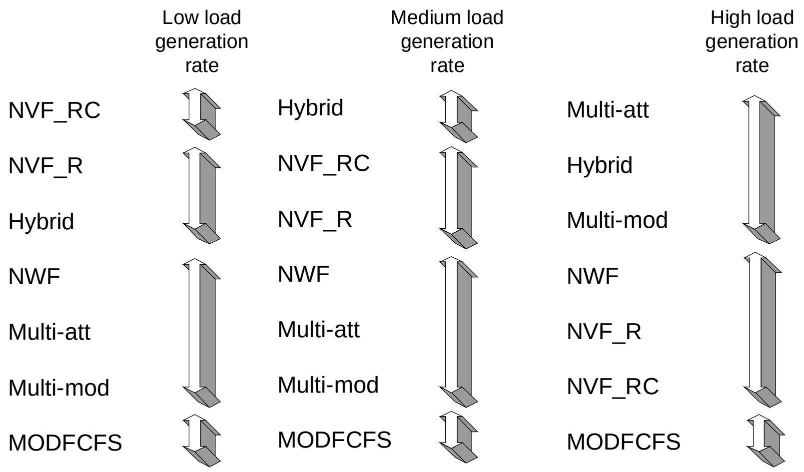


Figure 9 The overall ranks of dispatching rules

The dispatching rules are simple and can be easily implemented in practice. They perform quite well in most of cases. However, we can still improve the system performance further by implementing more complicated scheduling systems. A dynamic scheduling system, which can take more available information into account and schedule vehicles dynamically, may obtain a better performance. This research problem will be tackled in our future research.

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