Design of Distributed Route Based on Un-utility Coefficient under an Uncertain Transportation Condition at Logistics Center for Autonomous AGVs

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***Abstract*—The importance of automated guided vehicles is increasing in flexible manufacturing systems as they are flexibly to change in facilities and factory layouts. This study proposes a transport route that introduces a roundabout and a one-line through method based on the knowledge of transportation systems, to prevent interference between AGVs under irregular transport requirements and to achieve high transport efficiency. AGVs are required for irregular transportation, and stopping multiple AGVs. Due to interference between them during operation is a challenge that should be prevented because it will stop the production line and reduce production efficiency. The locations where speed differences occur are where the AGVs receive and deliver the materials to be transported. We will apply the knowledge of traffic engineering to improve the efficiency of transportation, and also adopt indices obtained from the knowledge of traffic engineering to evaluate transport efficiency.**

***Keywords*—Automatic Guided Vehicle, AGV, transportation system, traffic engineering, one-line through method**

I. INTRODUCTION

With the change in market needs, production systems have shifted from small-mix, high-volume production to large-mix, low-volume production as represented by the flexible manufacturing system (FMS). Also many organizations that use FMSs have used AGV systems for moving products from one workstation to the other [1]. However, in an FMS, the entire production system is controlled hierarchically as a large-scale challenge, which makes it difficult to respond flexibly to changes in the environment, such as the inability to easily change the equipment and layout of the factory once the system has been established, and the inability to stop part or the entire system if the production schedule is disrupted by a sudden accident or machine failure. Once the system is established, it is not easy to change the equipment and layout in the factory. To deal with these challenges, variable-species and variable-volume production systems have been proposed. For example, there is an autonomous decentralized production system [2][3] in which the components of the production system have autonomous decision-making functions. Among the components of these systems, the role of automated guided vehicle (AGV) transport systems, which control the flow of goods within a factory, is expected to become increasingly important. In addition, there has been research on autonomous AGV movement (e.g., a transport system wherein the AGV autonomously generates a route and moves to the destination without any guide [4] or autonomous driving guidance to avoid obstacles in a dynamic environment [5]). There is a growing need for AGV automation technologies in many industries ranging from manufacturing to service. An AGV transport system is a system that comprehensively controls and manages information related to AGVs. The design of the system and its operational strategy can result in a considerable difference in production efficiency. Although AGVs can flexibly respond to various transport conditions, when multiple AGVs are in operation, production efficiency can be reduced, owing to interference challenges between AGVs. Therefore, it is important to develop algorithms for system design and research operational strategies to ensure efficient and stable transportation. Therefore, extensive research is being conducted to realize autonomous systems, such as strategic control methods that consider the flexibility and optimality of AGV transport systems [6], AGV behavioral determinism using future predictive reasoning for challenges [7], simultaneous scheduling methods for machining machines and multiple-load AGVs using genetic algorithms [8]-[12], and cellular automaton methods that can reproduce phenomena in complex systems based on local neighborhood laws [13][14]. Research is also being conducted on autonomous AGV travel, such as transport systems that allow AGVs to autonomously generate routes and travel to destinations

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without guidance [15], and autonomous travel guidance to avoid obstacles in dynamic environments [16].

However, recently, cross-industrial exchanges have been actively performed in order to create new knowledge in the industrial world, and attempts have been made to apply and develop knowledge from various industries. In the field of academic research as well, new attempts are being made to mimic the superior functions of living organisms, such as "biomimetics," and these attempts are being applied to material and structural design in industry[17]-[19]. Therefore, based on the knowledge of production engineering and transportation engineering, which are different research fields, an AGV transportation system that can more efficiently reduce the interference between AGVs and transport goods will be studied by introducing a one-line through system[20], which is utilized especially on single-track railroad lines to increase the speed of the lines, to the AGV transportation system.

Recently, AGVs have been introduced at locations other than production plants, such as Amazon's logistics base and Amazon Kawasaki FC [21]. At these distribution sites, AGVs automatically shelve products that have been ordered online. The number of shelves in a distribution center varies depending on the type of business, but one online shopping business manages approximately 5000 - 10000 types of products and has 7000 - 30000 shelves to store them. In addition, the number of customer order slips per day is approximately 30000. Therefore, there is a strong urgency for an AGV transport system that can create a shipping plan that meets the delivery date of the customer's order, and that can respond to an environment in which the point of origin and destination of the transported items differ each time. Under such circumstances, it is considered effective to apply the two aforementioned system mechanisms described above to AGVs in order to reduce interference between them and improve transportation efficiency.

In this study, we introduce a one-line through method, which is one of the transportation system mechanisms, at the intersections of the transportation routes and at the pick-up/drop-off (P/D) stations, where the materials to be transported are handed over, and verified the effect of introducing the transportation system mechanism on the interference time between AGVs is verified. The total inefficiency index that evaluates train scheduling from the viewpoint of users' benefits [22][23], which represents the efficiency of resource allocation, is also used to verify the transport efficiency of incorporating transportation system mechanisms in each transport route.

II. Theory of Transportation System Organization

A. Similarities between Transportation and Transport Systems

To mimic the knowledge of the transportation system to the transport system, it must be assumed that the transportation system in the transport system has good mobility characteristics and the surrounding environment is similar. Therefore, we first compared the transition between production and transportation systems as presented in Table I. In the field of production systems, there is a need to evolve from the small-mix, high-volume production system put to practical use by the Ford Motor Company, to the large-mix, low-volume production system put to practical use by the Toyota Motor Corporation, and then to the variable-mix, variable-volume production system. However, in the field of transportation systems, steam engines were born during the Industrial Revolution, followed by buses and cabs, which improved passenger transportation services. In Japan, the first railroad line between Shimbashi and Yokohama opened in 1872, followed by buses in 1903 and cabs in 1912. The history of the transportation system is longer than that of the production system, and it is thought that the transportation system has evolved to an optimal state by overcoming various challenges. Furthermore, as markets need to diversify, more flexible systems are emerging to meet them, and the environmental conditions are likely to be similar.

Recently, there has been a strong demand for an AGV transport system that can create shipping plans that meet the delivery dates of orders from customers of variable types and quantities, and that can respond to environments in which the point of origin and destination of transported items vary from time to time. In such a situation, several AGVs travel irregularly in the system, and interference between AGVs frequently occurs at P/D stations and intersections in the transfer route where the speed difference between AGVs is generated. Therefore, it is considered effective to introduce the interference prevention mechanism introduced in the transportation system to the AGV system.

TABLE I. Transition of Traffic System and Manufacturing Systems.

	Traffic system	Manufacturing System
The 18th century	Watt steam engine appearance	
The 19th century	1872 The railway opens a business	
The 20th century	1903 The bus opens a business	1946 Manufacturing method of a large amount of small kind
	1912 The taxi opens a business	1970 Manufacturing method of a small amount of several varieties

B. Job, AGV, and Guide Path Requirements

The Job generation and transport settings in this study are indicated in (1) and (2), respectively.

(1) The point at which the job is generated at each P/D is determined randomly. Here, P/D (Pick -and-drop station) is the point where the AGV delivers jobs.

(2) It is assumed that the destination of the job is random and not known until the AGV receives the job.

Items (1)–(7) express the behavioral rules and constraints of the AGV and the conditions of the travel lanes.

(1) The driving lane is basically a single lane, single direction guide path.

(2) When a job is generated, the AGV closest to the location where the job is generated and that has not received a command will pick it up.

(3) The AGV travels the shortest route to the destination.

(4) AGVs are not allowed to reverse or go backwards in the travel lane.

(5) AGVs cannot overtake other AGVs.

(6) AGVs are not aware of the location and status of other AGVs. Therefore, they cannot take a detour route to avoid deadlock.

(7) The number of jobs that can be carried by one AGV is limited to one.

The state of the AGV is shown in (a)–(c) below.

(a) S_1: AGV is in the state of picking up the job generated by the command.

(b) S_2: The AGV is transporting the job.

(c) S_3: The AGV has finished transporting the job and is waiting for the command.

C. *One-line-through Method (OTM)*

The one-line-through method refers to the wiring of the track for waiting facilities and passing trains in a single-track section of a railroad, as illustrated in Fig. 1. The straight side of the track is utilized regularly for both the upper and lower trains, and the curved side of the track is utilized only for passing and overtaking. For example, an ordinary train is evacuated to the curved side, and a superior train, such as a limited express, is allowed to pass on the straight side. This is used to increase the speed of the line by allowing passing trains to pass on the straight side. In this study, we introduce this system at the P/D station, where AGV speed differences and interference between AGVs occurs. This is expected to reduce the interference between AGVs that are loading and unloading materials at a P/D station and those that are passing through the P/D station and transport materials to another P/D station.

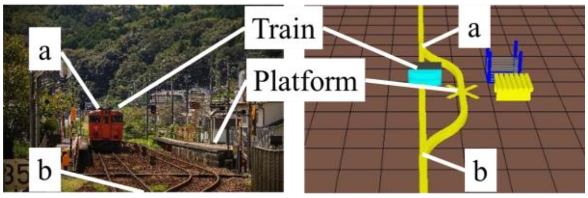


Figure 1. One-line through method.

III. Introduction of Transportation System Knowledge into AGV Transport Systems

A. *Application of Transportation System Mechanism in Transportation Routes*

One of the important indices in AGV systems is the transfer efficiency of the material to be transferred. To improve efficiency, the time between S_1 and S_2, as indicated in the previous section must be considered. Minimizing interference between AGVs when picking up and transporting items will improve the efficiency of transportation by ensuring that items can be transported without delay. Interference between AGVs occurs at the point where the speed difference between the AGVs occurs and at the intersection where a collision occurs. In the conventional loop system, the point where the interference occurs is in front of the P/D station where the AGVs load and unload the materials to be transported. Therefore, a one-line-through method of the proposed transportation system mechanism is introduced at each P/D station.

B. *The Index That Evaluates Train Scheduling from the Viewpoint of User's Benefit (E_f)*

The AGV system must be able to transport goods to their destinations efficiently. The same is true for railroad schedules, and the ideal railroad schedule from the user's point of view is one that does not keep passengers waiting and arrives at the destination quickly. In fact, the morning commuter rush in Japan is world-famous, and in recent years, the challenge of commuter rushes has become increasingly serious, as several people are forced to commute for long hours owing to the expansion of commuting areas. To address the challenge of commuter rushes, it is natural to first consider the benefits to the operator (number of cars, number of crew members, route facilities, etc.). However, when evaluating the desirability of the schedule from the user's point of view, quantitative evaluation is not conducted. Therefore, we quantitatively evaluate the benefits to users, which have not yet been evaluated quantitatively. In Japan, the first application of such a concept was a user-side evaluation study of buses, a medium-volume track system, and a monorail as alternatives in Momohanadai New Town near Nagoya [24][25]. We represent a train schedule as a network, and consider the user's train selection behavior as a route selection behavior on the network. In this way, criteria such as boarding time, degree of congestion, waiting time at boarding and intermediate stations, and waiting time for transfer can be expressed as link costs in the network when users select a train. Thus, the disutility incurred by a user under a certain train schedule is calculated as the sum of the product of the link traffic volume and link cost on the network. Unlike the road traffic network, the network created here is a space-time network with space and time on the horizontal and vertical axes, respectively. In creating the network, we classify the behavior of the passengers. Each of the following actions (1)—(9) is represented as a link in the network:

(1) Leave your home and arrive at the station. (O link)

(2) Board a train at a station. (Boarding link)

(3) Travel between stations by train. (Operating link)

(4) A train stops at a station. (Stop link)

(5) Get off the train at your destination. (D link)

(6) See off the train at the station without boaring. (Seeing off link)

(7) To get off a train to transfer to another train at a station before the destination. (Transfer link)

(8) Wait for the next train. (waiting link)

(9) At the station where the rendezvous is occur, transfer from the first arriving local train to the second-arriving honor train. (Waiting link)

However, the waiting for the waiting link in (9) means that the later-arriving honor train departs before each station stops training. In this case, the honor train stops at this station and is distinguished from the waiting link in which each station-stop train waits for the honor train to pass.

Fig. 2 illustrates a simple example of a three-station, three-train train schedule. The first station is the starting station, and the trains are numbered from the first station to the last station as one station, two stations, etc. The trains are numbered from the first station to the last station as one, two, etc. The trains are numbered in the order of departure, assuming that there is no layover or waiting. In this diagram, trains one and three both stop at each station, and train two is an express train that passes through station B. In such a schedule, a network such as that shown in Fig. 3 is created. The classification of the links in Fig. 3 is illustrated in (1) —(9).

(1) ◎→◇: O link

(2) ◇→○: Boarding link

(3) ○→○:Operating link

(4) ○→○:Stop link

(5) ○→●:D link

(6) ◇→■:Seeing off link

(7) ○→■:Transfer link

(8) ■→◇:waiting link

(9) There is no waiting link because there is no waiting in the diamond in Fig. 3.

In this way, we consider the flow of users as the link traffic volume. Using this approach, the total disutility index Ef can be formulated as Eq. (1).

$$E_{\mathrm{f}} = \frac{\sum_{\mathrm{a}} c_{\mathrm{a}} x_{\mathrm{a}}}{\sum_{\mathrm{rs}} q_{\mathrm{rs}} \cdot (L_{\mathrm{rs}} / V_{\mathrm{ref}})} \tag{1}$$

Here, the numerator ca in Eq. (1) is the cost of link a, and x_a is the flow of link a. In the denominator, q_{rs} is the traffic volume between OD pairs rs, L_{rs} is the distance between stations between OD pairs rs, and V_{ref} is the basic tabulated speed. If we take time as the cost, the numerator is the time it takes to travel from the starting point (point O) to the destination (point D), and the denominator is the time from the starting point to the destination. This means that the closer the value of the total disutility index is to 1, the better the transportation for passengers, and the more quantitative the evaluation of the schedule can be.

Train No.		1	2	3
Train type		Local	Express	Local
Station A	Dep.	703	704	705
Station B	Arr.	706	↓	708
	Dep.	707	↓	709
Station C	Arr.	710	709	712

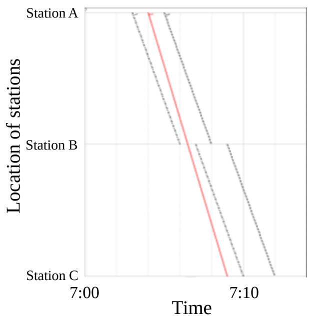


Figure 2. The example of a railroad schedule.

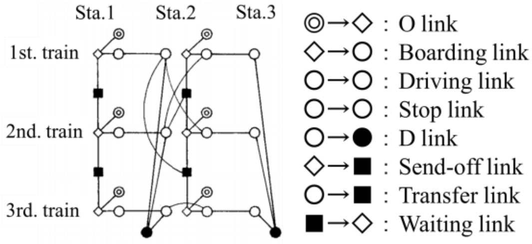


Figure 3. Space-time network in railroad schedule.

C. *Index Applied to the AGV System (E_{fa})*

A variant of the total inefficiency index indicated in Eq. (1), which is well known as a useful parameter to estimate the traffic railway efficiency, is used to evaluate the transport efficiency of an AGV system, and a variant of the total inefficiency index that can be implemented in an AGV system is formulated in Eq. (2).

$$E_{\mathrm{fa}} = \frac{\sum_{\mathrm{n}} t_{\mathrm{n}} x_{\mathrm{n}}}{\sum_{\mathrm{ab}} q_{\mathrm{ab}} \cdot (L_{\mathrm{ab}} / V)} \tag{2}$$

Here, t_n in the numerator is the time actually spent traveling between P/D stations, and the cost of the system is taken as the time required for transport between P/D stations. The cost of the system is the time required to transport goods between P/D stations. x_n is the number of goods transported between P/D stations. In the denominator, q_{ab} is the amount of AGV traffic between the P/D stations, Lab is the distance between the P/D stations, and V is the travel speed of the AGV. The ratio of the actual time required for the AGVs to transfer the material to the ideal time without considering the interference between the AGVs is calculated to evaluate the transfer efficiency. The ratio of the time required for the AGVs to transfer the objects to the ideal transfer time without considering the interference time between AGVs is calculated to evaluate the transfer efficiency. The index E_{fa} when applied to an AGV system also has a value of one, which means that the transport efficiency is better.

IV. Experimental Method

A. *Purpose of the Experiment*

The purpose of this study is to investigate the effect of introducing a one-line through method into the transfer route on transfer efficiency. By considering the loading and unloading times of the materials to be transported, which had not been considered before, various parameters that affect the values of the transfer efficiency, such as the average speed of the AGV, are generated. By focusing on each of these parameters, we quantitatively evaluate whether the introduction of the one-wire-through system contributes to the improvement of the AGV system transportation efficiency. To verify the effect of introducing a one-line through method, we conducted an experiment with a fixed number of four one-line-through methods. To investigate the effect of the parameters related to the transfer of the materials on the transfer efficiency, the parameters to be changed are the interval between the generation of the materials and the time related to the transfer, such as the loading and unloading time of the materials. The simulation was performed using the same transfer route.

B. *Experimental Device*

In this study, we utilized QUEST (ver. D5R19), manufactured by DELMIA, as the simulation software illustrated in Fig. 4. The data output from this production simulator includes the simulation time, average utilization rate of element (a component of the logistics route such as the AGV, point where the job originates, and destination), average time spent on the job, maximum waiting time, minimum waiting time, and total number of jobs that have or passed. Using this production simulator, the operating status and results are displayed in real time, allowing the user to visualize the transfer process of each AGV and to identify challenges that need to be addressed to a highly efficient transfer. In addition, the relationship between shape and distance can be altered to a relationship between the time and speed of the AGV.

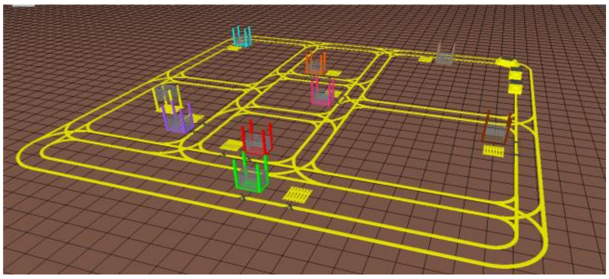


Figure 4. QUEST (manufactured by DELMIA).

C. *Setting up a Transport Route*

A transfer route is created to study the effect of the introduction of the one-line through method on the transfer efficiency. Simulations are performed for layouts with and without the one line-through-method. The original guide path without the one line-through-method is illustrated in Fig. 5 as the original layout. To create a layout in which the one-line-through method is introduced to each P/D section of the original layout, we decided to introduce the one-line-through method with a wait, which was efficient in our previous study. Fig. 6 illustrates the layout of the OTM-E layout with one-line-through method. Fig. 7 illustrates an overview of the one-line-through method with standby. In a previous study, we simulated a layout with a one-line through method, and determined that AGVs that had completed their transfers kept stopping at the P/D at the end of their transfers, preventing subsequent AGVs from unloading their loads. Therefore, we improved the conventional model, as illustrated in Figs. 7(a) (b). After arriving at the pick and drop points, the AGV unloads the material to be transported and moves to the evacuation point in front of the pick and drop points to avoid a drop in transport efficiency. All the one-line-through methods introduced in this simulation are the improved one-line-through methods illustrated in Fig. 7(b).

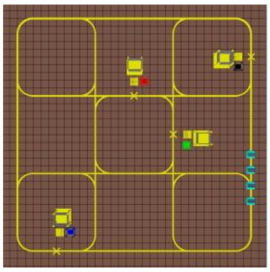


Figure 5. Original layout.

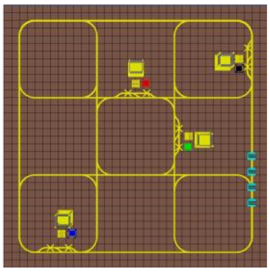


Figure 6. OTM-E layout.

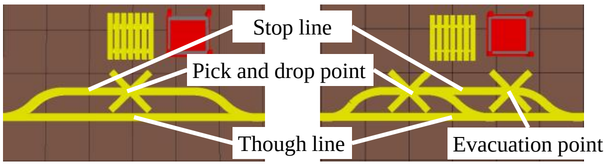


Figure 7. Improvement of OTM.

V. EXPERIMENTAL RESULTS AND DISCUSSION

A. *Effect of AGV Average Speed on Transfer Efficiency*

When the time required for loading and unloading is considered, the average speed of the AGV alters. However, the calculation method employed in Eq. (2) does not consider the average speed of the AGVs; hence, it is not possible to accurately calculate the transfer efficiency. Therefore, we attempt to accurately calculate the transfer efficiency by calculating E_{fa}, which considers the average speed of the AGV. By considering the time required to load and unload the cargo, the amount of time that the AGV travels at a standstill increases, and the calculation assuming that the AGV is traveling at the standard speed of 11 m/min would result in a large error. Therefore, we calculate E_{fa} by taking the average speed of the AGV during the simulation. The simulation is conducted under the experimental conditions presented in Table II.

TABLE II. EXPERIMENTAL CONDITIONS.

Operation time T [s]	22800
AGV velocity v [m/min]	11
Number of AGVs	4
Number of P/Ds	4
AGV length [m]	1.6
Loading time [s]	0, 10, 20
Unloading time [s]	0, 10, 20

The average speed of the AGV was calculated as shown in Eq. (3).

$$V_{ave} = \frac{V_{ref} \cdot t_{run}}{t_{sim}} \tag{3}$$

Where, V_{ave} is the average speed of the AGV, V_{ref} is the reference speed of the AGV, t_{run} is the running time of the AGV, and t_{sim} is the simulation time. Fig. 8 illustrates the average speed of the AGV calculated for each loading and unloading time. The longer the loading and unloading times, the more time the AGV has to stop at the P/D. This is considered to decrease the average speed of the AGV, which may affect the transfer efficiency, and the lower the average speed, the lower the transfer efficiency. The next step is to calculate E_{fa} using the average speed of the AGVs and compare the transport efficiency. To introduce the average speed of the AGV transport system, it is necessary to modify the method of calculating E_{fa} as expressed in Eq. (2). The formula for calculating E_{fa} can be modified for this simulation, as expressed in Eq. (4).

$$E_{agv} = \frac{t_{re} \cdot n_c + \frac{L_{rs}}{V_{ave}} \cdot n_d}{n_d \cdot \frac{L_{rs}}{V_{ref}}} \tag{4}$$

where, t_{re} is the dwell time of the products at P/D, n_c is the number of products generated, and n_d is the number of products transported. Fig. 9 illustrates the relationship between the interval between the generation of materials and total inefficiency index under each condition obtained from the simulation, and E_{agv} is calculated using Eq. (4). Furthermore, Fig. 8 illustrates that the smaller the average speed of the AGVs, the lower the transfer efficiency. This indicates that the transfer efficiency can be accurately calculated by introducing the average speed of the AGV into E_{agv}.

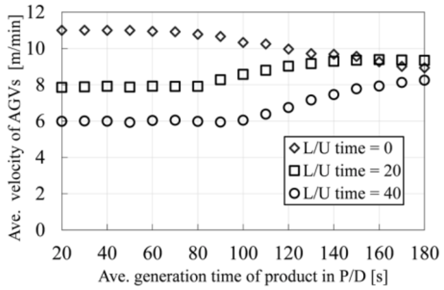


Figure 8. The relationship between the Vave of AGVs and average generation time of product in P/D.

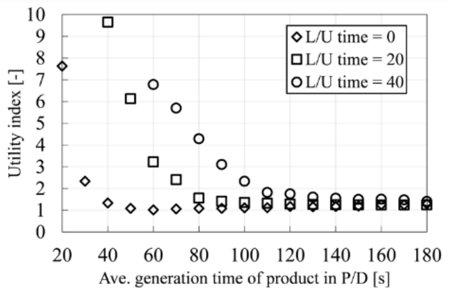


Figure 9. The relationship between blocked travel time and average generation time of product in P/D.

B. Evaluation of Transport Efficiency by Introducing a Single Line Through the System

In the previous section, we examined the effect of the one-line-through method on the transfer efficiency, considering the time required for loading and unloading the materials to be transferred. Although it was determined that the introduction of the one-line-through method improved the transfer efficiency, the degree of improvement in transfer efficiency was not evaluated. In this section, the E_{agv} is calculated based on the timetable of an actual line, and the effect of the introduction of a one-line-through method is examined. This section examines the effect of the introduction of a one-line-through method based on the trend of the E_{agv}.

In the previous section, we adopted the average speed of the AGVs to calculate E_{agv}, which enabled us to accurately calculate the transport efficiency. Using this calculation method, we simulated the layout illustrated in Figs. 5 and 6, and E_{agv}. Fig. 10 illustrates the relationship between the interval between the generation of materials to be transferred and the E_{agv} for each layout. It can be observed that the introduction of one-line-through method into the transfer path is effective when the interval between the generation of materials to be transferred is large.

The reason for the reversal of E_{agv} when the workpiece generation interval is small is thought to be related to the average speed of the AGVs. Fig. 11 illustrates the relationship between the average speed of the AGVs in each layout. The average speed of the AGV changes with the introduction of the one-line-through method, starting at an interval of approximately 60 s.

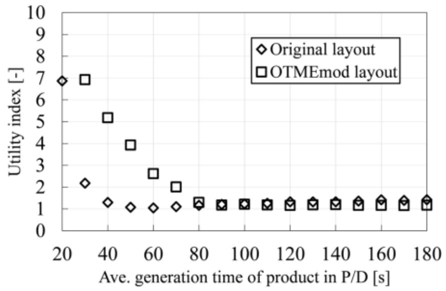


Figure 10. The relationship between E_{agv} and the average generation time of product in P/D.

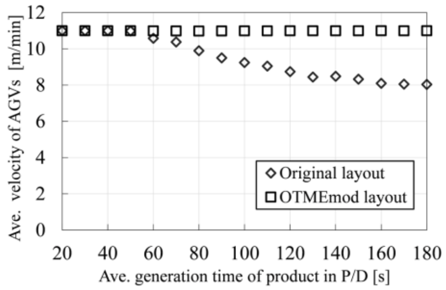
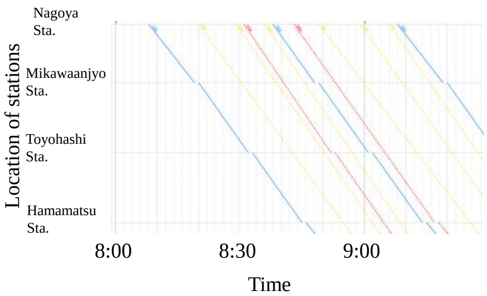
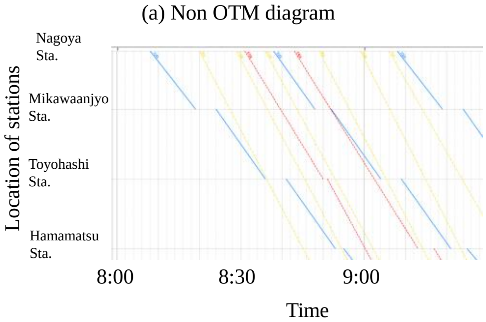


Figure 11. The relationship between the V_{ave} and the average generation time of product in P/D.

Although we have been able to calculate the E_{agv} correctly, we have not been able to evaluate the degree of improvement in transportation efficiency owing to the introduction of the one-line-through method. Therefore, we calculate the E_{agv} using the timetable of a railroad line where the one-line-through method was introduced, and investigate the effect of its introduction. In this study, E_f is calculated using the timetables of the Kintetsu Kashihara Line (Kashihara-jingumae – Yamato-Saidaiji, a local area railroad service, providing railway network including various types of limited express trains at Kansai region in Japan) and the Tokaido Shinkansen (Nagoya – Tokyo, a high-speed railroad service, providing more than 10 routes of bullet service across Japan) as examples. Both lines have one-line-through methods at intermediate stations. The E_f is calculated using OuDia, which is a software program for creating diagrams assuming that there is no through train system at intermediate stations. The E_f was calculated for the case where one-line-through method exists and for where no one-line-through method exists. Fig. 12 illustrates a diagram of the Tokaido Shinkansen. (a)is the timetable assuming that there is no one-line-through method on the route, and (b) is the actual timetable where the one-line-through method has been introduced on the route. Table III presents the effect of the one-line-through method on E_f. It was found that the decrease in E_f was greater for the Tokaido Shinkansen timetable, which has more stations with the one-line-through method. In addition, the effect is smaller on the Kintetsu Kashihara Line, which has only one station with one-line-through method. The improvement in E_f is similar to the improvement in E_{agv} when the one-line-through method is introduced to the AGV system. Therefore, it can be said that the introduction of the one-line-through method to the AGV system is effective.



(a) Non OTM diagram



(b)OTM diagram

Figure 12. Diagram of the Tokaido Shinkansen.

TABLE III. EFFECT OF THE ONE-WIRE-THROUGH METHOD.

	Non OTM diagram	OTM diagram
Kintetsu	1.09	1.06
Tokaido Shinkansen	1.20	1.03

VI. CONCLUSION

We focus on a variant of the total inefficiency index E_{fa}, which is well known as a useful parameter to estimate the traffic railway efficiency, to estimate the AGV transport system. If Modified inefficiency index E_{agv} is calculated using the reference speed of the AGV, we cannot accurately calculate the transport efficiency using that index. However, by introducing the concept of the average speed of the AGV into the E_{agv} calculation, we can obtain an accurate transport efficiency.

The average speed of the AGVs is considered to be a parameter that affects E_{agv}. In addition, the effect of the introduction of the one-line-through method on transport efficiency can be seen from the example of actual schedules.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Naoki HARADA and Takuma NAKATANI conducted the research; Naoki HARADA analyzed the data and wrote the paper; all authors had approved the final version.

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