Study on Efficiency Measurement Technique for Container Handling Equipment – Application to Hybrid Straddle Carrier.

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Abstract: The Kyoto Protocol came into effect in 2005, and actions for prevention of global warming are strongly desired in many industry sectors in Japan. Green House Gas in logistic activity in port is emitted by ship during anchorage and cargo gears during cargo handling operations for ship and so on. Kashii Park Port Container Terminal in Fukuoka-Japan is tackling this problem by employing low emission handling equipment such as Hybrid-type Straddle Carrier (HSC). Hybrid model of SC (HSC) is introduced in early 21st century as a part of Green House Gas reduction in container handling application. However, measurement of its efficiency is needed for its optimal utilization. In this paper, we study effect of HSC which utilized combined system of battery-powered system and electric generator system in reducing energy consumption and gaining regenerative energy. The energy efficiency of HSC is estimated through analyzing the actual operating data at container terminal. In aggregate, the experimental result showed average fuel consumption of 18.5 l/h and average state of charge of 8.4 A.h obtained from regenerative energy by lowering container motion.

Key Words: *hybrid straddle carrier, energy efficiency estimation, data capture and analysis*

1. INTRODUCTION

Container terminal, serving as nodal link between container shipping and hinterland transportation has high activity inside the terminal which involving various machineries. Since Kyoto Protocol came to effect in 2005, an enormous effort is ongoing to tackle GHG problem especially in the developed country (APEC - Maritime Expert Groups, 2009). A cost effective yet technologically-represent approach is needed to overcome this issue as well as maintain sustainable development of the terminal.

Large portion of activity in container terminal is undeniably the container handling by yard machineries. It serves as the flexible carrier-bridge for export and import container as well as responsible for pre and re-marshalling activity within the yard. Straddle carrier (SC) is one type of handling equipment for in-yard operation that considered as the optimal system for medium and large container terminals, when movement flexibility and high accessibility are required. It can achieve storage capacity of 750 TEU per hectare when stacking 3-high and able to cover all round operation (apron-to-transfer point).

For a direct straddle carrier system, up to 10 SC are required to handle various handling activity, while less than 5 are required when the relay straddle carrier system or combination with transfer crane or tractor-trailer for yard operation is applied. One of main disadvantage is that SC has comparably higher maintenance and energy cost than it’s complementary. To meet Kyoto Protocol targets, reduce in fossil fuel dependency by employing lower emission handling equipment and optimize machinery operation is mandatory.

Standard for efficiency measurement for each handling equipment in container terminal has been established, usually comes in the form of annual performance which then be compared to other terminal or the previous year performance. More accurate type of measurement is by examining the average operational performance, particularly in the form of fuel economy, handling rate, and regenerative energy (hybrid model). However, it is difficult to measure the exact value and the relation between operational behavior and its impact to performance.

With the introduction of hybrid (diesel-electric) model of straddle carrier (HSC), an observation can be made to see its operational performance other than shop test by the manufacturer. Earlier study by Hangga and Shinoda (2012) regarding HSC efficiency showed potential for improvement in operation technique of HSC to optimize its utilization as environmental-friendly machine. This study explains the development of appropriate technique to measure handling equipment's operational performance based the information observed on daily basis operation. Obtained result may serves as consideration for better operation behavior aimed to achieve lower energy consumption of handling equipment. In addition, an insight in energy loss and gain from various motions in operation were examined.

2. MATERIALS AND METHODS

2.1 Study Area

Kashii Park Port Container Terminal (KPPCT) in Fukuoka Prefecture, Japan is one of container terminal operated by Hakata Port. Occupied 22,3 ha area, this medium sized terminal has two principal quay berths with 600m quay length at -13 m depth, 4 gantry cranes equipped with latest technology, yard area with 8,964 TEU storage capacities, and utilized 17 straddle carriers as main handling system in container yard-apron operation with 5 hybrid carriers has joined the fleet (Hakata Port Terminal Co., Ltd., 2011). KPPCT utilize straddle carrier direct system where all in yard operation depends on the reliability of its conventional and hybrid model of straddle carrier. Therefore, an optimal combination of SCs and HSCs is needed to increase its operation efficiency.

2.2 Design of Experiment

As container handling activity maintain to be the largest portion of work in the container terminal, the operational performance of handling equipment is highly exposed and pressured to perform certain standard in daily operation. To perform the performance measurement without sacrificing normal operation of HSCs, a methodology to measure the power output of Hybrid S/C during operation is introduced. First, movement patterns are designed for experiments. A fixed movement patterns are important as base of measurement because it is difficult to measure the average handling performance of SC as its activity vary with circumstances. There are also different horizontal and vertical movements produced from the wheels and spreader, adding to its motion complexity.

Extraction of information during experimentation was conducted by developed data logging system. A voltage data logger is installed in the programmable logic controller inside the engine room of HSC. The logging actuate automatically at the time it catch voltage signal from the motions of HSC. Some items that represent operational performance were automatically recorded and stored as separate waveform data that can be analyzed later on. In addition, visual analysis was employed by attaching video recorders on various angles to complement the reading and interpretation of waveform data.

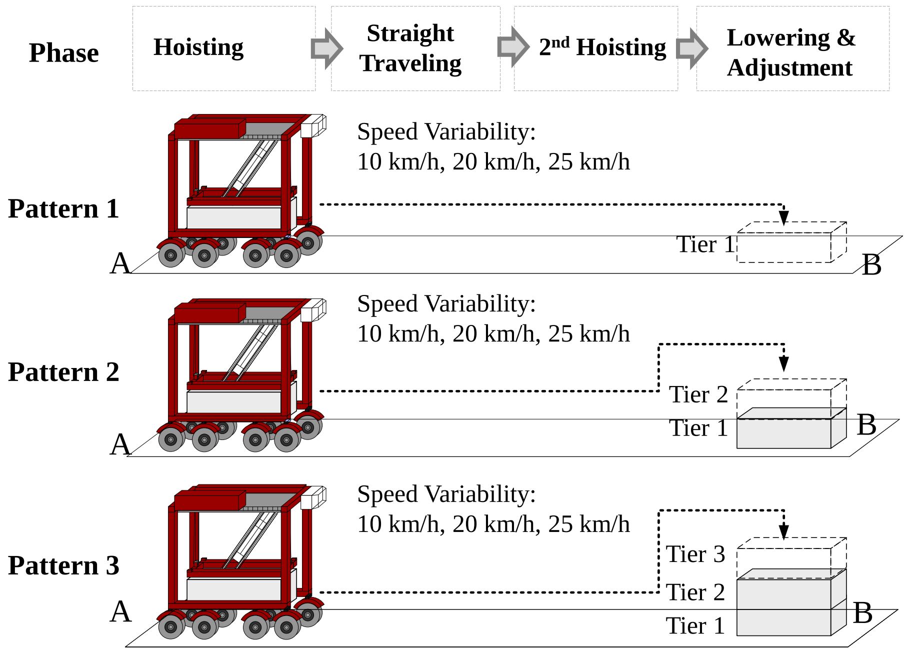


Figure 1 HSC Movement Pattern

2.2.1 HSCs Movement Patterns

Figure 1 depicts the movement patterns for HSC that is designed for experimental purposes. Basically, HSCs hoists a container with load, then travel from point A to B. After reach point B, it will lowering the container and adjust it into stacking area. Variables that will change during the experiments are traveling speed and stacking position (up to 3 Tier). When stacking a container into 2nd and 3rd tier, before reaching point B, it will have to hoist the spreader to adjust the height to stacking position. It is a standard procedure in SC/HSC operation, as during traveling, container must be placed on designated center of gravity of the machinery for stability purposes. The motions in this experiment are divided into several basic motions: hoisting-lowering motion and traveling motion.

2.2.2 Machine Performance Measurement by Voltage Logging

Voltage data logging is the measuring and recording of physical or electrical parameters over a period of time. Data loggers are used in a variety of applications such as in-vehicle data logging, environmental monitoring, and machine condition monitoring. Jokiniemi *et al*. (2012) examined the use of voltage signal captured from fuel level sensor and claimed it inexpensive, easy to install and did not require any modification to the system. In the field of container terminal operation, voltage logging method was proposed by Shinoda *et al*. (2009) to obtain gantry crane driving information and spreader motions such as winding up and down, traversing, and adjusting container to cell guide. The voltage signal was recorded per 100 ms and the logger is installed to PLC (Programmable Logic Controller) in the engine control room.

To capture the output of the engine, battery and generator of HSCs, continuous and temporal measurement of voltage output during designed movement patterns. Voltage signals were recorded using data logger HIOKI LR8400-20 at recording interval of 20 ms and voltage resolution of 0.5 mV in the 10 V range (HIOKI product catalog). The loggers itself were installed on the driver cabin with cables connection to sequencer in engine control room and throttle angle in the cabin. Figure 2 shows the installation and data recording diagram.

Table 1 Measured items, range and output from voltage logger

No.	Measurement item	Measuring Range	Output Voltage
1	Output current of battery	±500 A	±10 V
2	Lifting motor speed	±2000 RPM	±10 V
3	Traveling motor speed	±4000 RPM	±10 V
4	Engine speed	0 - 2000 RPM	0 - 10 V
5	Weight	0 - 40 Ton	0 - 10 V
6	Fuel Consumption	0 - 70 L/h	0 - 10 V

The data logger captured various loads from different parts of the HSC instrument and produced an isolated multi-channel waveform based on measurement list shown in Table 1. For measurement of fuel economy, the amount of fuel used per hour (l/h) is measured instead of distance (l/km) since S/C will need to reach several designated speed and run constantly for some time. Motor traveling speed, is measured in RPM (revolution per minute) to annotates rotational speed of mechanical component of the engine crank.

The waveforms from voltage measurement which based on the movement patterns are then converted into real value. Recorded waveform data for each channel is exported to spreadsheet into CSV and then converted to real value by calculating the integral value of signal waveform as illustrated in Figure 3. Mathematical expression of the calculation is as follow.

$$ACV = \left(\left(\sum |di| \times \Delta t \right) \div n \right) \times \left(\frac{M}{O} \right) \quad (1)$$

where:

n = Total number of data items

di = Data on channel number i

Δt = Sampling period

M = Max measurement range

O = Max output voltage

ACV = Average Channel Value

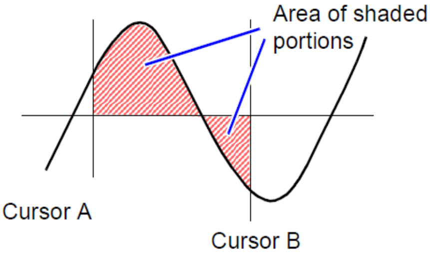


Figure 3 Illustration of of ACV

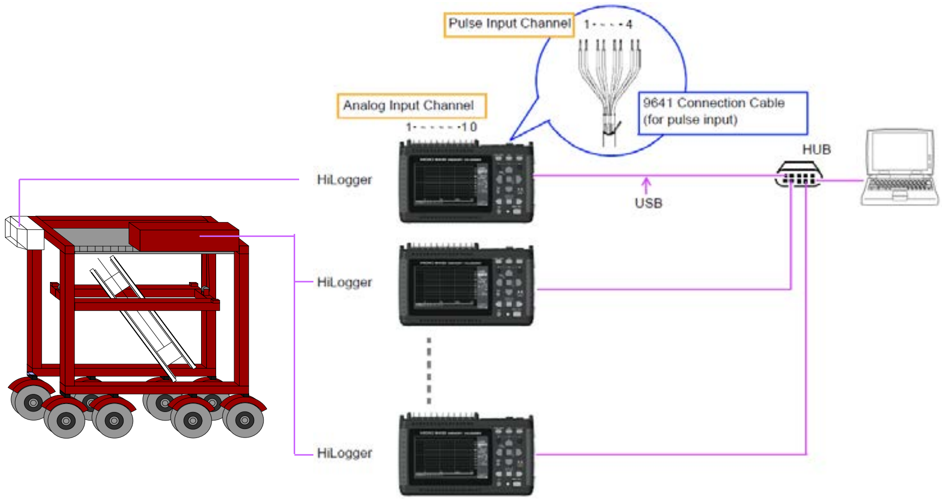


Figure 2 Voltage logger installation and data recording diagram

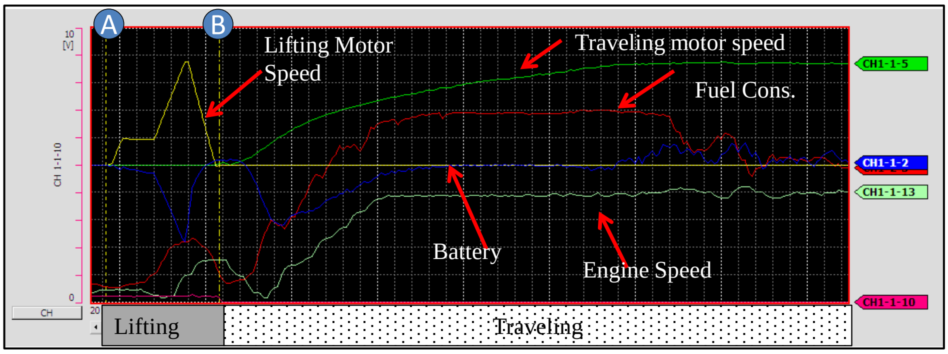


Figure 4 Screenshot of waveform data gained from data logging

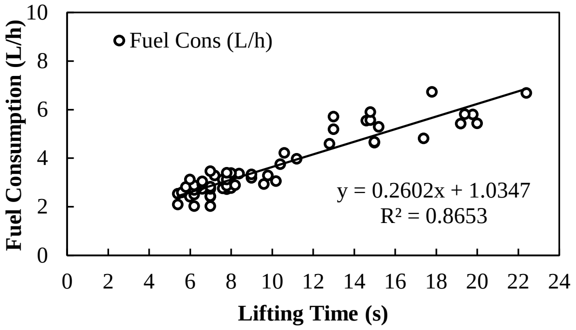

Figure 5 Screenshot of visual video record from various angles of HSC

Figure 4 depict the screenshot of the logger utility software to show several waveform data simultaneously under specific time measurement. The x-axis is the time elapsed and y-axis is the voltage range for each measurement variables. Since HSC conduct several types of vertical and horizontal motions, waveform for each motion was analyzed separately.

2.2.3 Video Recording

An additional measurement tool is needed for separating every phase when reading waveform data especially when there is ambiguity of operational movement. Reading of waveform data is difficult since it includes many motions and often in parallel with each other. A complementary method is introduced to help analyzed the waveform efficiently. In complement to data logging system, video recorders were installed inside SC main control room captures driver activity and to SC surrounding from various angles as shown in Figure 5. Ambiguous waveform data were able to be explained clearly by comparing the recorded video and waveform data on the same time stamp.

But application of video recorder was expensive and it has the limitation of memory and battery life. It is not efficient to apply such complementary method to analyze many container handling machineries operated in the container terminal. In future development of this measurement method, the authors would like to use GPS application to show spatial data of straddle carrier movement inside container terminal in lower cost.



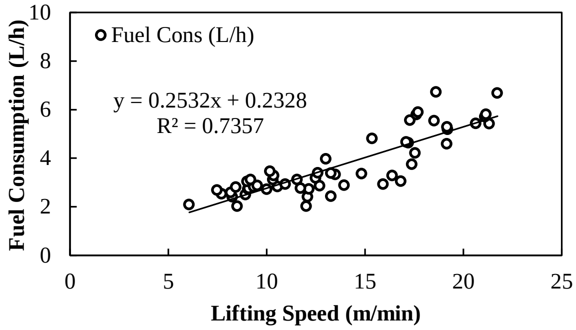


Figure 6 Fuel consumption rate of HSC under various hoisting speed

3. DATA ANALYSIS

2.1 Hoisting and Lowering Motion

Hoisting and lowering process is reciprocal in vertical movement of containers and thus cannot be analyzed separately. Moreover, it is most significant in the efficiency of straddle carrier as well as other vertical handling equipment in container terminal. Hoisting motion is marked as positive signal value and vice versa. Hoisting motion requires energy and by that it shall consume fuel oil during the process. From the analysis of the data, average hoisting time is 10.4 s. with linear hoisting speed of 13.6 m/min during laden condition, a figure that is slightly lower than the design specification of 21.6 m/min (TCM Corporation, 2012).

Relation between hoisting speed and time to fuel consumption rate during hoisting-lowering motion can be seen in Figure 6. Increases in lifting speed of spreader may slightly increase the consumption rate by twice. It can be implied that fuel consumption rate can be reduced by lower lifting speed. However, lifting speed will also have impact to the number of container moves per hour, and faster lifting speed means shorter handling time. Therefore it is necessary to show also the relation between handling time and amount of fuel to handle one container. Condition of container is also an important aspect that is needed to be considered. To show the real handling performance, only laden container is examined in this experiment.

UNCTAD standard presented by Thomas and Roach (1987) for lifting speed is 8-18 m/min while TCM Corporation (2012) stated that the HSC used for this experiment expected to have maximum lifting speed of 21.6 m/min. Our analysis of experimental data shows lifting speed ranging from 6.0 – 21.6 m/min and lifting time ranging from 5.4 – 22.4 s. The average fuel consumption for lifting motion only is 5.6 l/h with average lifting speed of 13.5 m/min and lifting time 10 s. One cannot assume that faster lifting speed is better for the operation of straddle carrier because the trade-off between amounts of energy used and container handling rate. We can say that the current operation of HSC in Kashii Park Port Container Terminal shows an average performance of energy use compared to both standards above.

Lowering motion of HSC on the other hand is best associated with gaining some regenerative energy in the process. Less energy is needed, but some energy can be gained harnessing the external force from gravity. From total of 61 hoisting-lowering motions data that had been analyzed, charging level reach an average of 8.44 A for all designed pattern, which can compensate the energy loss from battery discharge during hoisting motion which reach the average level of -14.65 A. The average fuel consumption for lowering motion only is 2 l/h which is lower than the fuel energy for hoisting motion.

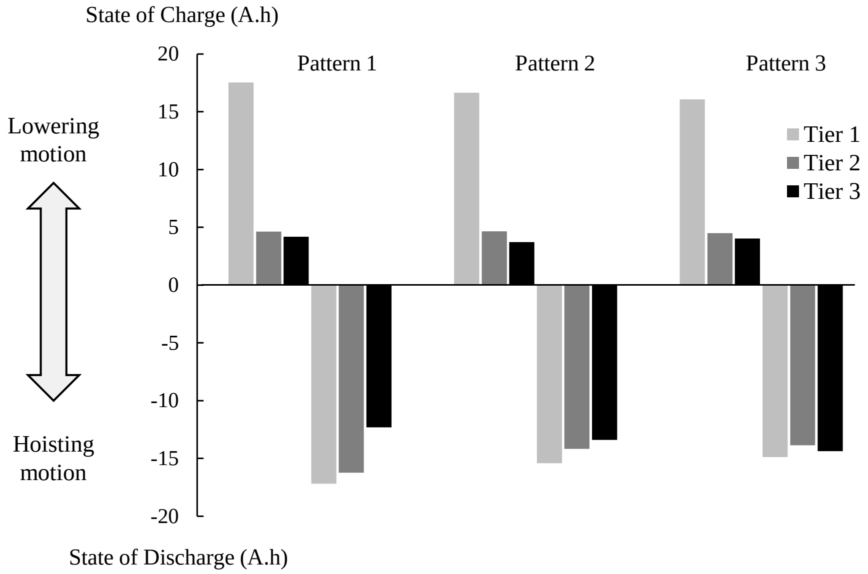


Figure 7 Battery charge and discharge level during hoisting-lowering motion

From Figure 7 it can be implied that regenerative energy is best gained from lowering motion to Tier 1, while less can be expected from lowering to Tier 2 and Tier 3. The energy gained from lowering to Tier 1 is almost equal to the energy loss when hoisting from the same spot. Therefore, we can expect high energy saving by implementing HSC during this motion.

2.2 Container Adjustment

Container adjustment motion is refer to the adjusting motion during lowering a container to trailer-chassis or on the top of other container in the stacking yard. In this study, a detail effect of adjusting in various lowering time and speed during adjustment process were analyzed. As container adjustment process is also included in lowering motion, it is important to separate the adjustment process to analyze only the lowering and hoisting motion in the waveform data. In the waveform, there will be a constant signal value at some time on the lowering motion, and after that the container adjustment motion will begin to start. Figure 8 illustrate the separation between lowering motion and container adjustment motion when reading lifting motor speed signal.

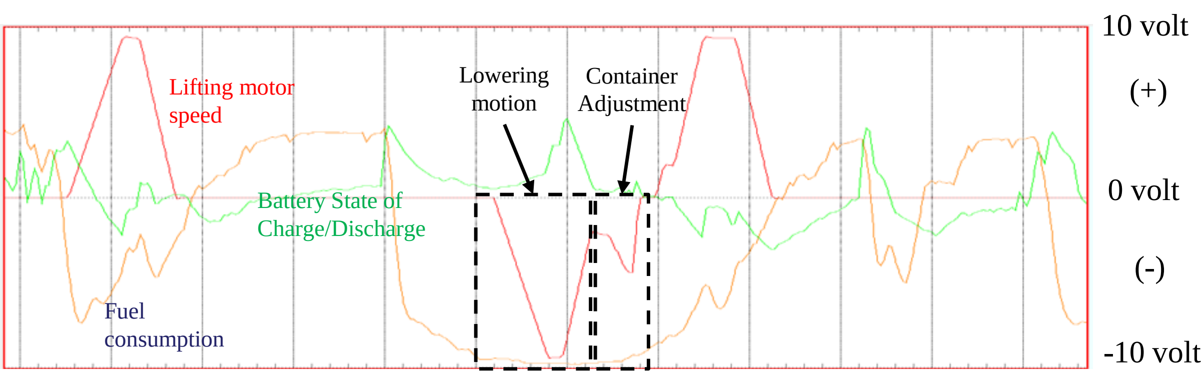


Figure 8 Separation of lowering and container adjustment motion in waveform

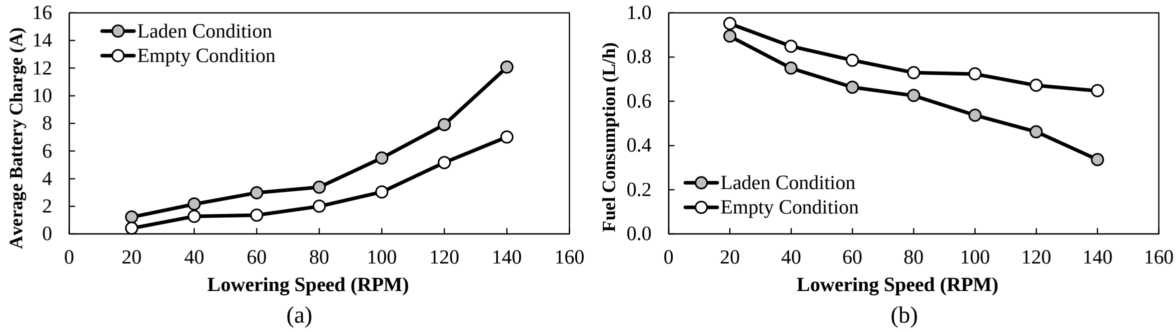


Figure 9 Impact of lowering speed to operational performance during container adjustment

Container adjustment time distribution frequency that is recorded from all experiment shows that adjustment time ranging from 1 to 8 second, with average adjusting time is 4 to 5 second for laden condition and empty condition respectively. However, less significant relation can be shown between adjustment time and battery charging rate and fuel consumption. Battery state of charge on the other hand is significantly proportional to the adjustment speed where it increases sharply after 100 RPM as shown in Figure 9(a). Average fuel consumption rate during container adjustment process is 0.66 L/h, where there negative relation with the increase of adjustment speed, ranging from 20 to 160 RPM as shown in Figure 9(b). It can be infer that faster container adjustment motion is best to gained instantaneous charging. In addition, fuel consumption rate will become lower with the increase of lowering speed.

2.3 Traveling Motion

Traveling motion refer to the horizontal movement of HSC during operation including straight traveling, cornering and any maneuver conducted from one point to another in order to catch or deliver the container. Because HSC is basically designed to transport container, only traveling motion during laden condition is examined, while motions during empty condition is ignored due to constraint given in the movement design pattern.

The traveling speed is already set based on practical service speed; 10 km/h, 20 km/h, and 25 km/h. The expectation is that appropriate service speed which expresses better trade-off between energy gain and loss can be determined. Energy analysis of traveling motion under various traveling speed infer that average fuel consumption rate is increased almost by twice for change in speed from 10 km/h to 25 km/h. Average fuel consumption rate for all design speed are 7.5 L/h, 14.8 L/h and 17.8 L/h respectively as shown in Figure 10.

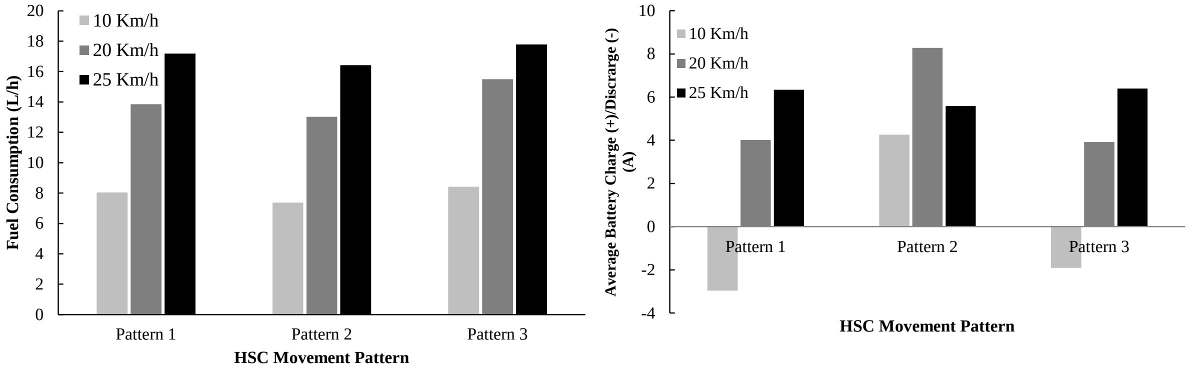


Figure 10 HSC operational performances under various traveling speed

Table 2 Hybrid Straddle Carrier Performance Indicator

Motions	Working time	Average State of Battery Charge (+) / Discharge (-)	Average Fuel Consumption (L/h)	
	%	(A.h)	l/h	%
Horizontal Motions	66.4%	-3.4	9.7	53%
Vertical Motions	33.6%	-14.7 (H) / 8.4 (L)	8.8	47%
Total	100.0%		18.5	

Note: H= Hoisting, L=Lowering

The expected energy trade-off from battery charging is meet less expectation compared to the level of charging that can be gained from lowering motion. However, higher traveling speed is expected to increase the battery charging level from wheel rotation up until 6 A. The results infer that average traveling speed should be preferable during normal operation. HSC may travel in long distance during a working day and slower speed can be associated with low containers handling rate. But increase of speed must be considered carefully as it also will increase fuel consumption rate.

2.4 Overall Performance of Hybrid Straddle Carrier

Thomas and Roach (1987) presented the main operation and maintenance feature of container handling system is the fuel consumption, in which straddle carrier is to consume as much as 20 l/h with favorable 12 container moves/h, while the standard from HSC maker is 18 l/h with 15 container moves/h. These figure of fuel consumption covered the overall motions straddle carrier movement while the standard fuel consumption figure for vertical motions, including hoisting and lowering is not exposed.

Our experiment by dividing the HSC motions allowed us to shows the fuel consumption for different state of motions, as shown in Table 2. Our experiment shows a figure of 13 container moves/hour with average fuel consumption of 8.8 l/h for both hoisting and lowering motions and 9.7 l/h for traveling motion.

As the advantage of diesel-electric machinery, a figure of battery state of charge and discharge were able to obtain through the experiment. In total, the advantage of hybrid type of straddle carrier shows obtainable regenerative energy by 8.4 A.h through lowering motion. These regenerative energy is able to compensate the loss from lifting motion (-14.7 A.h) and can be stored in rechargeable battery storage of HSC for different purpose of utilization. As for horizontal motions, it is still difficult to distinguish the advantage of energy charging because random oscillation of battery state of charge and discharge showed in the waveform.

Comparison of HSC (diesel-electric) and conventional SC (fully diesel) were not able to be conducted in current time because of different characteristic of machinery and electrical equipment. It is still difficult to implement voltage data logging system in diesel type machinery in the same manner to diesel-electric machinery. In order to compare the performance, a similar standard of measurement need to be made and used. The author is now developing the measurement system for conventional straddle carrier in Kashii Park Port Container Terminal.

4. CONCLUSION

Efficiency measurement technique from daily basis operation enables us to indicate the level of energy gain and loss based on the relation between the operational behavior indicator such as traveling speed and level of stacking. Developed measurement method from combination of voltage logging system and video recording able create figure of performance indicator, such as fuel consumption and battery state of charge or discharge. From the analysis, some conclusion can be drawn.

(1). Apart from the widely used aggregate performance standard for straddle carrier, a segregation of motions during operation helps us to do detail analysis of its behavior and impact to operational performance. Type of SC motion can be categorized into horizontal motion and vertical motion. Because of the flexibility of movement, it is difficult to distinguish the performance for each category. Our developed method was based on the analysis of operational data and was able to show the average performance for each, and obtain reasonable figure for showing the relation between performance parameter of the straddle carrier

(2). The average performance for Hybrid Straddle Carrier gained from analyzing the experimental data are shows a figure of 13 container moves/hour, average fuel consumption of 8.8 l/h for both hoisting and lowering motions and 9.7 l/h for traveling motion. For vertical motion, average battery state of charge is 8.4 A.h and state of discharge is -14.7 A.h.

Some policy implication are suggested for better HSC operation based on the analysis

(1). Average hoisting speed is preferable as fuel consumption rate is proportionally increased with the speed where no regenerative energy can be gained during this motion.

(2). Higher lowering speed is preferable during normal operation especially in laden condition as weight and gravitational force help to reduce dependence of energy from fuel oil.

(3). HSC is suggested to be utilized for receipt and delivery operation, as it lower until lowering motion until ground (Tier 1). The energy gain and loss from the spreader motion is canceling each other because of the presence of regenerative energy from lowering motion. Therefore, HSC is best employed in this type of operation to explore its environmental-friendly characteristic.

(4). Faster container adjustment motion is preferable to gain instantaneous charging, as average fuel consumption rate is also lower with the increase of speed. The implication may be introducing some guidance to the driver to be able to help locking the container position fast and precisely during adjustment.

(5). Average traveling motion should be preferable as HSC may travel in long distance during a working day because the increase in fuel consumption were examined to be too high compare to the energy gain from battery charging.

5. FUTURE REMARK

In the future, the authors would like to include application geographical position system in the efficiency measurement in accompany to the current technique in order to gain position information for better visual analysis of the operational performance. The concept of visualization and providing real-time monitoring is essential in the effort of finalizing this measurement method before it can be used in practical day-to-day operation. Also the authors planned to compare the performance of hybrid straddle carrier with conventional straddle carrier used in modern container terminal.

ACKNOWLEDGMENT

The authors would like to express their gratitude to Mr. Kazuhiro Hiyoshi from Hakata Port Terminal Co.Ltd and Mr. Shozo Takahashi from Uni Carriers for providing permission and help to conduct the experiments in Kashii Park Port Container Terminal, in Fukuoka, Japan. The authors also thank two anonymous reviewers for the insightful and constructive comments on the manuscript.

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