Motion-Based Energy Analysis Methodology for Hybrid Straddle Carrier Towards Eco-Friendly Container Handling System

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Abstract: This paper presents an in-depth energy analysis for hybrid straddle carrier to identify their energy consumption sources and discover energy reduction potentials. The methodology incorporates analysis of motions, performance data acquisitions by data logger, video analysis and spatial information analysis. Impact of various hybrid straddle carrier motions to energy consumption is presented and its total energy consumption is compared to diesel-driven straddle carrier. Subsequently, energy consumption model is calculated to grasp fuel coefficient associated to each motions that forms a movement of hybrid straddle carrier. Finally, prediction of energy use is calculated based on analysis of motion as a decision support system for container handling tasks.

Keywords: Hybrid Straddle Carrier, Motion Analysis, Energy Consumption, Port Operation

1. INTRODUCTION

Many container terminals have implemented strategies focusing on reduction of diesel fuel consumption while keeping its performance. The aim of all efforts is to make transport and logistics sector more sustainable. The issue is to discuss the relevance of energy consumption as a base for identifying energy efficiency potential in an emerging awareness of consumption, efficiency and associated costs of energy in maritime trade. Despite of automation, utilization of hybrid handling machineries is an alternative being carried out to reduce dependency to fuel oil consumption for yard operation. Moreover, performance of prime mover in container terminal in terms of energy consumption is an important factor relating to service competitiveness. Container yard undoubtedly is a good place to start energy reduction measures since it connects the sea side operation and hinterland operation.

The hybrid straddle carrier (HSC) is introduced as one of energy-efficient solution for yard operation in reducing emission in port towards green container terminal along with electric-rubber tired gantry. Energy conservation of diesel straddle carriers has been improved by applying hybrid technology to the machinery system. However, they are not in widespread use because the initial installation cost is relatively high and older technology equipment is remaining in service to complete its economic life. (APEC, 2009). Container terminals in Japan, Korea, Taiwan and New Zealand has initiated the use of hybrid handling machineries since 2007 and both of full-electric and hybrid machineries are in operation along with diesel-driven machineries. Particularly in Japan, the government has support the use of eco-friendly handling equipment since the enactment of Kyoto Protocol in 2005. The HSC prototype under evaluation in this study is one of tripartite project (government, industry, university) for promoting the use eco-friendly container handling system.
However, like any other new technology, the adoption level is slow. Container terminals are dealing with high investment risk without knowing the information regarding its performance. At current time, the performance comparison of hybrid straddle carrier to its predecessor in terms of energy reduction and efficiency only had done at shop test level. It is obviously important to measure actual performance as a step to evaluate the operation, distinguish drawbacks. Showing the advantage in quantitative approach is expected to enhance the adoption of new technology towards green container terminal. Therefore, a methodology to measure energy performance analysis

2. APPROACH ON PERFORMANCE ANALYSIS OF CONTAINER TERMINAL

Measurement of container terminal efficiency is of particular importance because they are vital to the welfare in the region and can reflect level of economic development in surrounding areas. Several studies have attempted to estimate performance of container terminal. The level of approach can be grouped into three categories based on level of detail measurement; overall terminal performance, operational system performance, and cargo handling gear performance. The results of the more detailed approach can be a complementary input for another approach from the bottom-up. This is highly important because measurement is related to accuracy and value of information.

Overall container terminal performance mostly focused on productivity indicators or evaluation of productivity and assessment of handling strategies. It has been evaluated by cargo handling productivity (Bendall and Stent, 1987) or overall throughput evaluation based on some historical benchmark (Talley, 1988). Performance indicators related to economic values (UNCTAD, 1975) and DEA panel data model are in the use to properly describe overall performance of container terminal (Cullinane and Wang, 2010). Collection of accurate data for the above mentioned methods is the problem in the terminal which has less record of operational activity, but close estimates can be made using port data available in public-domain internet website (Chu et al., 2013).

Operation performance examines examining the current and historical performance based on type of operation and measuring that performance against an established set of cost, schedule, and performance parameters. An example is the analysis of yard operation as a system. It has been done in many studies, notably by use of object-oriented simulation to investigates way to improve overall efficiency (Bielli et al, 2006; Yun et al. 1999), routing and dispatching of cargo handling equipment (Kim et al., 1999; Steenken et al., 1993; Ndiaye et al., 2008, Ku et. al, 2010)

On the other hand, measuring cargo handling gear performance as individual entity is difficult although it gives detail information on the behavior of equipment and its impact to the system efficiency. Useful information regarding detail performance is scarce and expensive to be retrieved. When applicable, detail analysis of container handling machinery performance will reflect how well the adoption of new technology as well as pointing the risk from its operation. The issue is difficulties actual acquiring performance data quantitatively, particularly for hybrid handling machineries. Yang and Chang (2013) and Yang and Lin (2013) analyze performance of hybrid machineries, particularly electric-rubber tired gantry crane (E-RTG) in Port of Kaoshiung, Taiwan. The comparison with older technology is also presented qualitatively. Effectiveness and efficiency gained from implementation of E-RTG as environmentally-friendly handling machineries is showed based on annual operation activity. However, types of operation that leads to energy reduction were not shown in the research. Moreover, similar approach relates to performance analysis of hybrid straddle carrier is not yet published so far.
From operational level analysis point of view, static view of production throughput is insufficient to disclose efficiency. Therefore actual measurement is the best way to address the scarcity of performance information. This research will mainly focus on developing methodology to deliver detail energy analysis of hybrid straddle carrier as a form of its performance.

3. HYBRID STRADDLE CARRIER SYSTEM

The hybrid straddle carrier (HSC) was introduced as uplift of conventional diesel-driven straddle carrier (SC) for yard operation in reducing emission in port towards green container terminal. Straddle carriers usually operates in combination with stacking cranes/transfer cranes and yard chassis in the container yard although in some terminal it can be used for apron side movement of container to supply the gantry crane. The type of hybrid straddle carriers that is examined in this study is a diesel-electric straddle carrier currently in operation at Kashii Park Port Container Terminal (KPCT), in Fukuoka City, Japan.

Important aspect of the hybrid system is their ability to regain energy through motion. When a container is lowered, the gravitational potential energy can be converted into an electric power called the regenerative power. It is stored in a power storage system composed of an electrolytic capacitor.
Table 1. Operation codes

<table>
<thead>
<tr>
<th>No</th>
<th>Codes</th>
<th>Explanation of operation code</th>
<th>Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Delivery</td>
<td>Moving a container from any stacking position in the Container Yard and deliver it to chassis waiting at Transfer Point.</td>
<td>CY-to-OC</td>
</tr>
<tr>
<td>2</td>
<td>Receipt</td>
<td>Catching a container from a chassis at Transfer Point and stack it on designated stacking position in Container Yard</td>
<td>OC-to-CY</td>
</tr>
<tr>
<td>3</td>
<td>Export</td>
<td>Moving a container from any stacking position in Container Yard and deliver it to apron under the gantry crane.</td>
<td>CY-to-GC</td>
</tr>
<tr>
<td>4</td>
<td>Import</td>
<td>Receive a container from gantry crane at the apron and stack it on designated position in Container Yard</td>
<td>GC-to-CY</td>
</tr>
<tr>
<td>5</td>
<td>Shifting</td>
<td>Stack and unstack of a container in Container Yard (yard preparation, re-handling, marshalling and spacing)</td>
<td>CY-to-CY</td>
</tr>
</tbody>
</table>

CY: Container yard, GC: Gantry crane, OC: Outside chassis

Figure 3. Motions of straddle carrier

This regenerative power is used for hoisting another container. HSC hybrid system is as outlined in the upper part of Figure 1, is composed of a diesel fuel generator and a lithium-ion battery to store the regenerative energy obtained during operation. When the load of the generator is increased during hoisting or state of traveling, the discharge is performed from the battery in order to support the output to the motor. Battery discharge has been performed via the control of pulse width modulation (PWM).

4. MOTION-BASED ENERGY ANALYSIS METHODOLOGY

As container handling activity maintain to be the largest portion of work in the Kashii Port Container Terminal, the operational performance of handling equipment is highly exposed and pressured to perform certain standard. HSC Performance measurement is carried out during normal operation of hybrid straddle carrier, and methodology to measure its operational performance is developed.

A methodology is defined to identify energy consumption sources and discover energy reduction potentials through performance data acquisition. It incorporates the analysis of motion, data acquisition coupled with spatial information to create comprehensive energy analysis. This research was formed by primary data acquired by experimentation since there are no record of previous academic paper discussed the collection of hybrid straddle carrier performance data. Firstly, motion of hybrid straddle carrier is defined. Secondly, performance data is acquired by data logging system. Thirdly, spatial information is collected by measuring geographic coordinate of hybrid straddle carrier in conjunction with data logging.
4.1 Analysis of Hybrid Straddle Carrier Motion

The first step to measure operational performance is by looking into detail of each operation. Straddle carrier movement is complex in nature and it is difficult to distinguish the performance only by looking at aggregate performance standard. Concept of segregation of motions during operation helps us to do detail analysis of its behavior and impact to operational performance. The result of the analysis is needed to determine energy consumption associated with the motion.

By looking at stacking yard as focus, general work of hybrid straddle carrier is categorized into operation codes as shown in Table 1, such as receipt and delivery (Chassis-CY operation), import and export (Ship-CY operation) and intra CY operation. Operation code is formed by a combination of motions which can be categorized into horizontal motion and vertical motion. Figure 3 depicted the relationship between operation codes and motions that forms it. We opted to analyze detail motions in order to examine energy use for every motion and to point out influential factors in every steps of operation as well as increase the accuracy of data collection. Furthermore, segregation of operation into motions will minimize ambiguity in analysis when examining complex movement.

Figure 4 shows data acquisition and analysis framework that were undertaken in this research. The energy analysis is conducted in two ways; firstly, the data is analyzed by manual separation of motion, then total work is analyzed. The analytically derived result is used to compare the performance of Hybrid-driven and Diesel-driven straddle carrier. In the second approach the database is reconstructed and energy analysis is visualize using simulation.
Table 2. Obtainable performance parameter by voltage logger measurement

<table>
<thead>
<tr>
<th>No</th>
<th>Measurement item</th>
<th>Range</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Output of converter</td>
<td>±500 A</td>
<td>±10 V</td>
</tr>
<tr>
<td>2</td>
<td>Output of battery</td>
<td>±500 A</td>
<td>±10 V</td>
</tr>
<tr>
<td>3</td>
<td>Lift motor speed</td>
<td>±2000 RPM</td>
<td>±10 V</td>
</tr>
<tr>
<td>4</td>
<td>Lift motor torque</td>
<td>±200 %</td>
<td>±10 V</td>
</tr>
<tr>
<td>5</td>
<td>Travel motor speed</td>
<td>±4000 RPM</td>
<td>±10 V</td>
</tr>
<tr>
<td>6</td>
<td>Travel motor torque</td>
<td>±300 %</td>
<td>±10 V</td>
</tr>
<tr>
<td>7</td>
<td>Throttle angle</td>
<td>0-100 %</td>
<td>0 - 10 V</td>
</tr>
<tr>
<td>8</td>
<td>Steering direction</td>
<td>forward/reverse</td>
<td>10V/0V</td>
</tr>
<tr>
<td>9</td>
<td>Hoist lever angle</td>
<td>0-100 %</td>
<td>0 - 10 V</td>
</tr>
<tr>
<td>10</td>
<td>Brake pedal angle</td>
<td>0-100 %</td>
<td>0 - 10 V</td>
</tr>
<tr>
<td>11</td>
<td>Engine speed</td>
<td>0-2000 RPM</td>
<td>0 - 10 V</td>
</tr>
<tr>
<td>12</td>
<td>Bus voltage (DC)</td>
<td>0-2000 V</td>
<td>0 - 10 V</td>
</tr>
<tr>
<td>13</td>
<td>State of Charge</td>
<td>0-100 %</td>
<td>0 - 10 V</td>
</tr>
<tr>
<td>14</td>
<td>Fuel Consumption</td>
<td>0-70 L/h</td>
<td>0 - 10 V</td>
</tr>
<tr>
<td>15</td>
<td>Weight</td>
<td>0-40 Ton</td>
<td>0 - 10 V</td>
</tr>
<tr>
<td>16</td>
<td>Twist lock</td>
<td>lock/unlock/10V/0V</td>
<td></td>
</tr>
</tbody>
</table>

Figure 5. Voltage logger installation and performance data acquisition

4.2 Data Acquisition by Voltage Logger

Performance data of hybrid straddle carrier is collected by data logging system. Data logging is a data acquisition system commonly used in scientific experiments and in monitoring systems where there is the need to collect information faster than a human can possibly collect and in cases where accuracy is essential. In this study, we use voltage data logger to measure and record physical or electrical performance parameters over a period of time.

Performance data acquisition by voltage data logger for container handling equipment has been investigated by Shinoda et al. (2009) to obtain gantry crane performance information. Hangga and Shinoda (2014) developed and tested a detail voltage logging procedures to extract more information concerning to performance. 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. The loggers were installed on the driver cabin with cables connection to sequencers that captures voltage outputs as shown in Figure 5.
The data logger captured various loads from different parts of the HSC instrument and produced an isolated multi-channel waveform based on parameter list shown in Table 2. Fuel used per hour (L/h) is measured instead of distance (L/km) since hybrid straddle carrier will need to reach several designated speed and run constantly for some time. Motor traveling speed, is measured in RPM (revolution per minute) to annotate rotational speed of mechanical component of the engine crank. It is difficult to distinguish type of motion by stand-alone voltage logger examination because hoisting-lowering and traveling motion is often in parallel with each other. Thus, 6-channel video recorders were employed to support waveform interpretation. Obtained information is saved in a USB and read using special application software that presents the data in waveform. Subsequently, all data are then exported to spreadsheet and converted into real value by calculating the integral value of signal waveform. Eq.1 was defined to convert the waveform into average channel value (ACV) during a specific motion. When a specific motion $M$ is detected, calculation area is constrained to the waveform signal between the cursor A and B as shown in Figure 6. Desired parameter $M$ value is gained from integration of the shaded portions, the value is divided by total number of data ($n$). The average value of integration is multiplied by conversion rate ($R_{max}/V_{max}$) to get the real value for each item.

$$\pi_{M,p}(ACV) = \left( \frac{\sum_{i=1}^{n} |d_p| \Delta t}{n} \right) \frac{R_{max}}{V_{max}}$$

(1)

where,
- $M$ : Type of motion
- $P$ : Type of measured items refer to Table 1
- $\pi_{M,p}(ACV)$ : Average channel value, restrict to type of motion and parameter
- $n$ : Total number of data items inside between cursor A&B
- $|d_p|$ : Data for parameter $P$
- $\Delta t$ : Sampling period
- $R_{max}$ : Maximum measurement range
- $V_{max}$ : Maximum output voltage
4.3 Use of Spatial Information for Analysis

Spatial information is beneficial to complement the comprehensive energy analysis, taking into account the association of motion and energy consumption. The container terminal studied in this paper is located in Fukuoka city of Japan; therefore the datum used for geographic coordinate data is Japanese Geodetic Datum 2000 (JGD 2000) Zone II – Fukuoka. GPS devices (PhotoMate 887, produced by Transystem) were used to measure velocity and traveled distance within 1s interval and accuracy of 0.05-0.1 m/s (95% probability).

Furthermore, NMEA output from geographic coordinate data of container terminal is transformed to plain Cartesian coordinate system as illustrated in Figure 7. Plain Cartesian coordinate data is used to produce plain map display of container terminal and movement of examined hybrid straddle carrier for depicting energy consumption in accordance to data logger output. The expected outputs of GPS measurement are listed in Table 3.

<table>
<thead>
<tr>
<th>No.</th>
<th>Measurement item</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Position - Latitude</td>
<td>JGD 2000 °North / °South</td>
</tr>
<tr>
<td>2</td>
<td>Position - Longitude</td>
<td>JGD 2000 °East / °West</td>
</tr>
<tr>
<td>3</td>
<td>Date Information</td>
<td>mm/dd/yyyy</td>
</tr>
<tr>
<td>4</td>
<td>Time</td>
<td>hh/mm/ss (AM/PM)</td>
</tr>
<tr>
<td>5</td>
<td>Distance from start</td>
<td>meter</td>
</tr>
<tr>
<td>6</td>
<td>Distance to next</td>
<td>meter</td>
</tr>
</tbody>
</table>

Figure 7. Conversion of geographic coordinate of container terminal to plain coordinate system

Figure 8. Use of rechargeable energy during horizontal motion
5. RESULTS OF MOTION-BASED ENERGY ANALYSIS

This chapter explains the energy analysis conducted by proposed methodology in earlier chapter. First, energy utilization based on motion is presented. Then, effect of working time and distance is discussed. Finally, hybrid straddle carrier performance can be compared with diesel-driven straddle carrier.

5.1 Energy Utilization of Single Hybrid Straddle Carrier from Analysis of Motion

There are 107 work data that were acquired by the data logger method on January and August 2014. Figure 8 illustrates fuel consumption graph for horizontal motion of hybrid straddle carrier from container unloading work acquired in January 14, 2014. Important parameters that were examined are energy storing and discharging and its relation to fuel consumption. The figure show evidence that stored energy is discharged in order to support generator load. Amount of discharge is controlled by pulse width modulator (PWM; refer to Figure 1) and this operation helps to reduce fuel consumption at the time stored energy is discharged, as shown in area A. On the other hand, the system switched to state of charge from wheel rotation during decelerates as shown in area B. This figure shows response of the hybrid system to support electricity and buffer oversupply of energy during horizontal operation. Amount of battery charge and discharge is measured by data logger, and voltage outputs for motion illustrated in Figure 8 are gathered for further analysis. Despite of complexity of motion, traveling motion can be noticed from its typical waveform, where traveling motor speed is increases. Additional video camera analysis is conducted to divide the cornering motion to straight traveling.

Figure 9 shows energy use characteristic during vertical motion such as hoisting and lowering spreader. Peak of hoisting and lowering motion can be seen from the hoisting-lowering graph. When lowering a container, gravitational force is converted to electricity and stored in rechargeable lithium-ion battery. Fuel consumption during lowering motion is essentially low and this motion possesses the main advantage of hybrid machinery system. The stored energy is discharged during hoisting a container to support work of generator, thus reduce fuel consumption during the early stage of hoisting motion. Analysis of vertical motion from waveform data is carried out by segregation of hoisting and lowering motion. Hoisting motion produced (+) value of hoisting motor speed and lowering motion produced (-) value. In addition, there is container adjustment motion that is incurred inside lowering motion which needs attention.
Investigation of HSC motions allowed us to show the fuel consumption for different state of motions. Figure 10 shows energy utilization based on working time, fuel consumption, and battery utilization. Work analysis was performed to exhibit HSC level of performance based on two motion categories; horizontal motions and vertical motions. Horizontal motion is represented by traveling motion while the other motion represents vertical motion.

Traveling motion has a high portion during operation, accounting for 66% from total working time. Its fuel consumption accounted for 12.1 L/h which is half of the average fuel consumption for all motions. On the other hand, hoisting motion accounted for 15% from total working time. However, its fuel consumption covers up to 31% or 7.2 L/h in average. Work analysis indicated that traveling and hoisting motion have an important impact on the fuel consumption. Further analysis that is interesting to be analyzed is modeling fuel consumption with respect to travel distance and examining the impact of stack height to fuel consumption when lifting up container.

Also important is the figure of battery state of charge and discharge for each motion. The advantage of the hybrid type of straddle carrier shows obtainable regenerative energy by 8.8 A.h through lowering motion. This regenerative energy is stored in rechargeable battery storage of HSC for supporting generator while hoisting the container. 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, but an average of -3.4 A.h was gained as average value from all data.

5.2 Effect of Working Time

Figure 11(a) shows the relationship between hoisting time and fuel consumption rate during hoisting-lowering motion. The horizontal axis shows various hoisting and lowering time and vertical axis shows fuel consumption corresponds to it. In order to grasp various conditions in operation, the analysis considers the load condition during the vertical motion analysis. Laden condition means there are full containers in possession during hoisting motion, and empty condition means that there is no container grasped by spreader.
Linear regression line written in the graph shows the relation between observed parameters. Fitted line plot shows the relationship equation where $x$ means hoisting or lowering time and $y$ means fuel consumption that corresponds to the increasing value of $x$. This figure is indicating that longer hoisting time will tend to increases fuel consumption particularly during laden condition. Load condition; laden or empty, are an important factors that relates to the increases of fuel consumption. However load condition did not have impact to fuel consumption even in longer time. The examined hybrid straddles carrier data has an average hoisting time of 10s. Considering the above result, it is interesting to further examine the impact of load condition based on container weight.

Figure 11(b) shows battery rechargeable level dependency to hoisting and lowering time. Horizontal axis of the graph shows hoisting or lowering time and vertical axis shows battery utilization level in Ampere that corresponds to it, whether for charge (+) or discharge (-). Linear regression line written in the graph is used to depict the relationship between the parameter, where $x$ represents hoisting or lowering time and $y$ represents battery utilization. Hoisting motion uses the stored energy during container lifting process. High level of battery discharge is needed to support high load of generator. Load condition also have impact to the amount of discharge, where discharge level in laden condition counted two times as much as empty condition. Nevertheless, the figure shows battery charge level increases proportionally with time when lowering in laden condition. Contradictive to hoisting motion, longer lowering time will give advantage to increases amount of battery charge.

Information about travel time for traveling under laden and empty condition is shown in Figure 12. It shows the travel time frequency every 10s. According to this figure, the cumulative percentage has a peak at 100s in laden condition is the average travel time 101s and it has well cohesive data. Travel time under empty condition peak between 50s to 60s with average travel time at 79s and data is more dispersed. Difference in time distribution pattern time indicates that there are different stacking strategies being implemented.
5.3 Effect of Travel Distance

Energy consumption for vertical motion is able to be noticed explicitly considering hoisting and lowering motion is standard motion for any kind of operation code. However, horizontal motion was vary by travel speed and distance. Since each operation consists of different range of horizontal motion, the pattern is more difficult to be seen. Horizontal motion inside each sample operation is extracted and analyzed as an independent motion. The relationships between variables were shown in Figure 13. The analysis were carried out from 186 straight traveling motion which derived from 23 delivery operations, 9 receipt operations and 7 shifting operations. Relationship of fuel consumption to traveled distance is important result and is used as basis for delivering model for fuel consumption of traveling motion. In order to depict effect of travel distance to the energy consumption, visualization of energy use of hybrid straddle carrier is carried out by combining result from motion analysis and spatial information from GPS data.

5.4 Visualizing Energy Analysis

There are potential uses of large amounts of experimental collected using our proposed framework. The information is quantitative and there are currently no tools available to extract and interpret this type of information. We decided that visualizing the energy consumption is a way to recognize systematic behavior of HSC performance by exhibiting its properties in a well-designed graphical display, thus enhancing the progress of research.

A java applet is made by Java programming language to animate energy use of hybrid straddle carrier corresponds to its movement in the stacking yard. The input of the program is reconstructed database in comma separate values, incorporating data logger output and GPS recorder output. Here we tried to visualize historical movement of the HSC and as a result, fuel map and battery utilization map can be displayed. Movement of HSC on the screen is based on coordinate updates and it allows us to see the energy consumption associated with it.

We were able to not only the behavior of HSC that consumed specific amount of fuel, but also the range of activities that were done within one day of operation. Figure 14 shows example of battery utilization map of examined HSC. Electric discharge is marked in red color and electric charge is marked in green color. The equipment move based on projected coordinate as time evolves, each performance parameters can be seen in bar chart that corresponds to the value in database. Behavior of hybrid straddle carrier for 8 hours working time is viewable and it is easier to notice the motion that leads to high energy consumption.
The feature of battery utilization confirm the explanation of Figure 8 and 9, where battery energy is charge before HSC do cornering motion due to decelerate and brake, meanwhile energy is being discharged when accelerates. Up to this point the authors has made an attempt to uncover hidden information from acquired data related to performance of HSC.

5.4 Comparing Hybrid and Conventional Straddle Carrier Performances

Container handling productivity data was collected from Kashii Park Port Container Terminal from period 2010-2014, consist of; operating hours, traveled distance, number of handled container, and amount of diesel fuel used. In addition, performance standard and result from other research were collected as comparison. Diesel-driven straddle carrier is to consume fuel as much as 20 L/h with favorable 12 container moves/h while examined hybrid straddle carrier consumed 23.3 L/h with handling productivity of 21 box/hr. 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

Comprehensive comparison of performance between SC and HSC based on similar monthly production output is shown in Table 4. Average value of working time for both hybrid and diesel straddle carrier under evaluation was 228 hours. Under similar monthly working hour and traveled distance, hybrid straddle carrier consumed an average of 5,297 L/month; break downed to 23.3 L/h, while straddle carrier consumed an average of 7,201 L/month; break downed to 31.9 L/h.

The comparison is intended to show reduction rate in energy consumption achieved by hybrid straddle carrier. Despite lower fuel consumption per hour, the table indicates hybrid straddle carrier has higher level of fuel efficiency than that of diesel type during the above described period. The table indicates that hybrid straddle carrier have 27.4% reduction rate of fuel consumption than diesel-driven straddle carrier. Its average handling efficiency is 0.2 L/box lower than that of diesel type, albeit lower figure of monthly container handling. Other than the result, we understand that hybrid straddle carrier is in service along with diesel-driven straddle carrier in the examined container terminal.
Nevertheless, the table shows that diesel-driven straddle carrier have higher production and handling rate than hybrid type. The authors were able to track the reason behind it using the constructed java program explained in section 5.3. HSCs were utilized mainly for receipt and delivery operation during evaluated duration, while SCs were utilized for export and import operation. Export containers are usually arranged in the marshalling area near to the apron and confirmed by the movement visualization. This resulted in SC has more moves and handling rate for similar working hour and traveled distance compared to HSC.

6. PREDICTION OF ENERGY CONSUMPTION AS DECISION SUPPORT SYSTEM

Fuel consumption is relevant as a base for identifying energy efficiency potential since main energy source from this equipment comes from diesel fuel. Reduction of fuel consumption for each handling operation is not only the task of operation planner but also on the hand of the handling equipment’s driver. Consequently, a model is made to predict future energy consumption that shows impact of any point-to-point movement inside the stacking yard to increase in fuel consumption. Then performance of the model is evaluated with actual data. Finally, prediction of energy use is presented as a decision support system.

6.1 Energy Consumption Model

Fuel consumption for horizontal motion is depends on the distance while fuel consumption of vertical motions is known per one movement. Therefore, distance model is made using CAD data of Kashii Park Port Container Terminal. Distance is measured between point-to-point inside the container yard and compared to acquired distance from GPS data. Cornering radius is assumed through the circumference distance of 4m and the cornering angle was 45 degrees. In addition, special motion when straddle carrier maneuver for placing the container into the container slot, called marshalling motion, is assumed to be 24m by analysis of actual data.

We use the distance model as a basis to predict the fuel consumption related to hybrid straddle carrier motion. Total fuel consumption is the summation of fuel consumption from vertical motion and horizontal motion respectively. $F_{\text{vertical}}$ is divided into hoisting and lowering motion. $F_{\text{lowering}}$ consists of two parts; pure lowering and container adjustment.
process. $F_{\text{horizontal}}$ is divided into straight traveling, cornering motion and marshalling motion.

\begin{equation}
F_{\text{total}} = F_{\text{vertical}} + F_{\text{horizontal}}
\end{equation}

\begin{equation}
F_{\text{vertical}} = F_{\text{hoisting}} + F_{\text{lowering}}
\end{equation}

\begin{equation}
F_{\text{horizontal}} = F_{\text{traveling}} + F_{\text{cornering}} + F_{\text{marshalling}}
\end{equation}

Here we evaluate the fuel consumption by using equation (2) to (4). There are 107 operation data involving receipt and delivery operation obtained from experiment on January 14, 2014 and August 14, 2014. Operation data is divided into motions and fuel coefficient $C_f$ for each motion was calculated as shown in Table 5. The authors were able to retrieve the information regarding loading condition particularly for vertical motion, however the difference of signal waveform for fuel consumption in horizontal motion are difficult to be distinguished by the current method. Recalling to Figure 11, movement in laden condition does have effect to increase in fuel consumption but empty condition have less significant impact. Therefore, the empty movement is not yet considered in current fuel consumption model. Stored energy utilization also known to have impact in reducing fuel consumption for hybrid straddle carrier particularly for hoisting motion. Therefore, fuel coefficients was assumed to include the advantage of hybrid machineries since all the data that formed the coefficient came from motion based analysis of hybrid straddle carrier system.

Furthermore, total fuel consumption of hybrid straddle carrier is calculated based on re-created routes. Fuel consumption is combined from each motion according to actual route as illustrated in Figure 15. To verify robustness of the model, 107 operation routes were re-created using the model and total fuel consumption for each operation was compared with actual fuel consumption from data logger.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|}
\hline
\textbf{motion} & \textbf{Coefficient} & \textbf{Unit} & \textbf{motion} & \textbf{Coefficient} & \textbf{Unit} \\
\hline
$F_{\text{hoisting}}$ & 0.2320 & L/motion & $F_{\text{traveling}}$ & 0.0019 & L/motion \\
$F_{\text{lowering}}$ & 0.0823 & L/motion & $F_{\text{cornering}}$ & 0.0486 & L/motion \\
$F_{\text{marshalling}}$ & 0.0449 & L/motion \\
\hline
\end{tabular}
\caption{Fuel consumption coefficient based on motion}
\end{table}

![Figure 15. Calculation of fuel consumption based on motion’s coefficient](image)
Figure 16. Verification of energy consumption model

(a) Fuel consumption model verification
(Rem: Deliver/Receipt – Lane Name)

(b) Travel distance distribution of model
(Num of data: 107 operation code)

Figure 17. Route options based on combination of motion for a selected operation

Figure 16(a) shows verification results of fuel consumption model for 32 sequential operations which is compared to measurement result by data logger. It shows that our model has good agreement with actual data at 8% error. Distance profile of measured operation is shown in Figure 16(b) showing that most of examines receipt operation are in lower total distance than delivery operation.

6.2 Prediction of Energy Use by Fuel Consumption Model

Amount of energy use by hybrid straddle carrier is relevant to the fuel consumption of the machinery. Therefore, prediction of fuel consumption for movement inside the yard is as important as the effort in reducing fuel dependency in container handling operation. Energy consumption model is used to calculate fuel consumption for any designated routes inside the stacking yard. In its application, spatial information data from actual operation were examined to investigate optimum route selection for the hybrid straddle carrier.

Figure 17 illustrates route option for specific origin-destination. HSC driver might chooses several path to reach destination. For example route 2 is the original path taken by the equipment. Route 1 should have been selected since it has the shortest distance hypothetically when consider single straddle carrier operation and negligible yard-traffic.
HSC driver may also take route 3 because the driver might see yard congestion and tried to avoid it. From the job task point of view, there are only origin and destination. However, from HSC driver perspective, more optimum solution can be achieved in terms of route options. We looked at room for improvement in operation in terms of providing HSC driver a guidance to select the best route that minimizes energy consumption.

Example of assessment of current hybrid straddle carrier performance in route selection is shown in Figure 18. Fuel consumption difference between for actual route and optimum route for 38 sample of sequential route is accounted for 10%, indicating actual route for straddle carrier might already good enough. However, some operation code shows significant reduction in fuel oil consumption due to re-routing option, notably operation no. 4 (delivery, 53% reduction), operation no. 5 (delivery, 41% reduction) and 15 (shifting, 67% reduction). Average figure of total fuel consumption in optimum condition accounted for 21.8 L/h, while calculation based on actual route accounted for 23.6 L/h. Reduction in cumulative fuel consumption when HSC driver always selected optimum route for re-calculation of 203 operation data accounted up to 21%. The author noticed that distance difference between route options lies on number of cornering motion.

Nevertheless, this study is focused on delivering decision making support system while giving some room for professional judgment by operation control room or equipment’s driver. It is important to always notify the user on how their decision can have effect in operation efficiency. However, as in any other efficient operation, safety factors are always be the first to be achieved. Since the HSC operation involves several carriers moving around in the container yard, the authors are aware of decisions taken by HSC driver might not resulted in the shortest route for a specific task.

Decision support system is needed that at least indicative in notifying implication of every decision that is going to be made. The challenge is to help choosing tasks for container handling inside the stacking yard with less cornering motion and assumed that there is no detour; predicted value of the fuel consumption is made display as illustrated in Figure 19, called as energy map. The starting point of hybrid straddle carrier in the figure is transfer point. According to this figure, Lane D, E, H, I is most likely be chosen as the next job order since the fuel consumption will be small. On the other hand, left-side of Lane A, right wing side of Lane B, and Lane M is less likely to be chosen due to higher fuel consumption. The
calculation of fuel map is basically from calculating the shortest travel distance from origin to potential destination, taking into account all motion that combines in making a route.

Estimation of energy consumption through fuel map is best coupled with straddle carrier routing algorithm when the value evolution of expected fuel consumption is timely-present and future handling task is known. When some rules are set for the hybrid straddle carrier to independently choose container handling task, the driver can be notified of risk and limitation based on fuel map while the equipment travels inside the stacking yard. Further reduction of fuel consumption related to the entire travel is expected to be achieved in this manner.

HSC driver have experience-driven decision making tools that is useful determining which straddle carrier should be assigned to a specific job. We propose assignment rule for straddle carrier takes shortest-travel-distance rule, which is a vehicle-initiated rule. The system measures the distance between pick-up locations to straddle carrier, added by distance between pick-up locations to target location and the assignment is based on the distance the HSC has to covers. The energy map then useful to notify HSC driver regarding predicted fuel consumption and it is interoperable in the terminal operating system. In this way, the driver can participate in the decision making process. Therefore the fuel map is made dynamic and changes contour as the HSC moves inside the container yard. For example, the user might not always take the shortest route due to traffic condition. In this case, the energy map is indicating how much fuel will be consumed when traveling to actual, yet longer route.

![Figure 18. Example display of energy map](image)

7. CONCLUSION

This study presents methodology for data acquisition of performance data in conjunction to motion-based energy analysis of container handling equipment. It serves as evaluation for adoption of new technology towards green container terminal. In order to analyze the acquired huge data, a set of parameter is made, and operation is categorized into operation codes including segregation of all motion that forms it. The idea of motion-based analysis is presented, aimed to alleviate the complexity of HSC movement and formalize the motions that form the process in operation. The methodology is tested on hybrid straddle
carrier operation, includes data logging, spreadsheet calculation, visual analysis, and spatial data collection. The implementation of the concept delivers a new approach in addressing the problems of measuring the performance of cargo handling gear.

The proposed methodology able to extract adequate information to determine energy consumption associated with the motion and pointed out behavior that relates to energy reduction. Analysis of motion successfully identified critical points in every motion that have impact to increase of fuel consumption as well as battery energy charge and discharge. Another investigation shows operation that corresponds to regeneration of energy. The stored rechargeable battery is used as buffer to high energy use and can be discharged if needed. In addition, analysis of spatial information enables an effortless recording of the velocity and location of the machine in determining fuel map and battery utilization map.

Subsequently, energy consumption model is calculated to grasp fuel coefficient associated to each motions that forms a movement of hybrid straddle carrier. A prediction of energy use is modeled using dynamic energy map based on shortest route calculation. The proposal outlined as a decision support system which can be interoperable with the development of terminal operating system for container handling tasks. As the yard situation is known not only by central control system, but also by the HSC driver, interoperability of the system could be enhanced by using the energy map, where the driver can be involved in the decision-making process to determine which straddle carrier should be assigned to the job.

8. FUTURE DIRECTION OF RESEARCH

The future research is unthinkable without further development of experimental framework to be more time-efficient to collect and analysis desirable data. For instance, recognizing motion pattern is time consuming. We also think that motion-based energy analysis provides us with better approach to cut down the complexity of machinery movement and we would try to apply it for another type of container handling equipment.

In terms of algorithm for energy map, we would try to take dynamic information like traffic jam or vehicle dependent restrictions into account. Solving the issue of appropriate deployment of HSC incorporating prediction of fuel consumption from energy map will be the next direction of our research. Another aspect that we want to consider is regarding the cost-benefit analysis that expressed as a payback period to provide more evidence in long-term advantage from investing in “greener” technology such as hybrid straddle carrier.

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REFERENCES


