Stacking Technologies for Intermodal Operations

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Design and operational features of yard gantry cranes and straddle carriers are explained, stressing in particular the progress made in the past 5 years. This equipment is reported to permit higher stack densities and require less operating space than other types of container-handling equipment. The straddle carrier, apart from fulfilling the double requirement of stacking and loading in a flexible fashion, is also considered an excellent vehicle for container transport. Current standards of engineering design, reliability, and maintenance characteristics have reached a high level. However, there is available no general or ultimate rule for system selection. Feasibility studies considering cost calculation and operational evaluation turn out differently under different conditions. Often the results are found to be quite close. The basic considerations of such investigations are outlined in this paper. The final choice of system and equipment, however, will remain with the user and this choice may sometimes be difficult. In any case there is excellent equipment to choose from in designing a container port or intermodal facility.

The economic efficiency of intermodal container operations is largely determined by three major factors:

- Geometric layout of the yard and organization of the intermodal terminal,
- Proper operation and maintenance of the facility, and
- Performance of container-handling equipment.

Major intermodal terminal container operations that provide the connecting link between the transport modes of water, rail, and road frequently require loading and stacking of containers along with the movement of containers between the points of loading and stacking in a yard storage area.

To accomplish this function the following major types of loading equipment are used as state of the art for the positioning of containers when loading or stacking:

- Ship-to-shore gantry crane,
- Yard gantry crane (larger span versions are sometimes referred to as bridge cranes),
- Straddle carrier, and
- Front- or side-loading vehicle.

For the movement of containers within the terminal or yard the following types of equipment are generally used:

- Truck tractor with trailer chassis,
- Straddle carrier, and
- Front- or side-loading vehicle.

Many operators consider that yard gantry and straddle carrier systems are generally today's two main competitors for use in large-scale terminal operations with a container-stacking requirement. The front- or side-loading vehicles may supplement this equipment for special activities and are frequently used in smaller operations where less stringent requirements in terminal space utilization and stack organization exist. The material that follows is based on the authors' familiarity with a particular line of equipment and should not necessarily be taken as all-inclusive.

A typical equipment matrix consisting of yard gantry cranes, straddle carriers, and tractor-trailers offers four principal operating combinations, all of which may be found in one terminal operation or another. The following table gives an example of combinations of positioning and moving equipment in a marine container facility (restricted to the yard operation) taking the ship-to-shore crane as a basic requirement. It specifies the four principal operating combinations.

Positioning Equipment:	Moving Equipment: Tractor-Chassis	Straddle Carrier
Yard gantry	Tractor-chassis/ yard gantry	Straddle carrier/ yard gantry
Straddle carrier	Tractor-chassis/ straddle carrier	Straddle carrier only

The variety of equipment in the table may be further increased by considering separately rail-mounted and rubber-tired yard gantries.

As a general rule, the tractor-chassis becomes the most economical transport alternative for moving containers distances of more than 1,000 ft in the terminal. However, careful evaluation is necessary because a "once-through" straddle carrier operation (quay and stack) is quite low in its manpower requirement and may eliminate the need for some tractor-chassis equipment.

Figures 1-3 are illustrative models that show the most common equipment combinations used in container terminals located at ports:

- An all-straddle carrier system (Figure 1),
- A tractor-chassis and straddle carrier system (Figure 2), and
- A tractor-chassis and yard gantry system (Figure 3).

Examples of these systems in actual use appear in Figures 4-7:

- All-straddle carrier operation in use at the Ports of Hamburg, Hong Kong, and Antwerp (Figure 4);

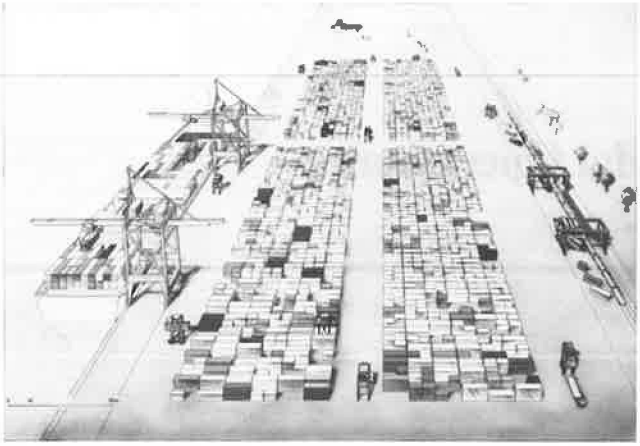

FIGURE 1 Model of shore-stack operation with straddle carriers.

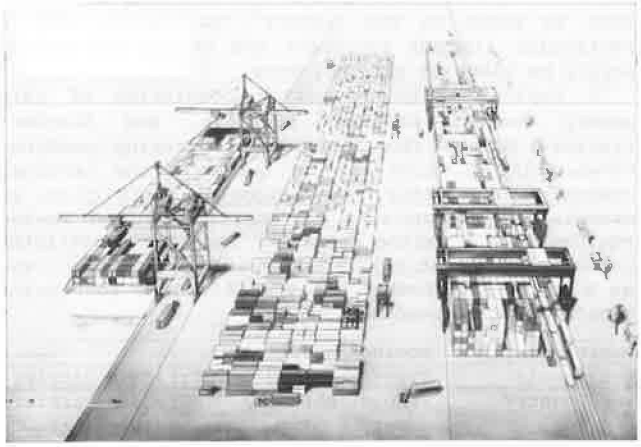

FIGURE 2 Model of tractor-chassis operation with straddle carriers and gantries for rail car service.

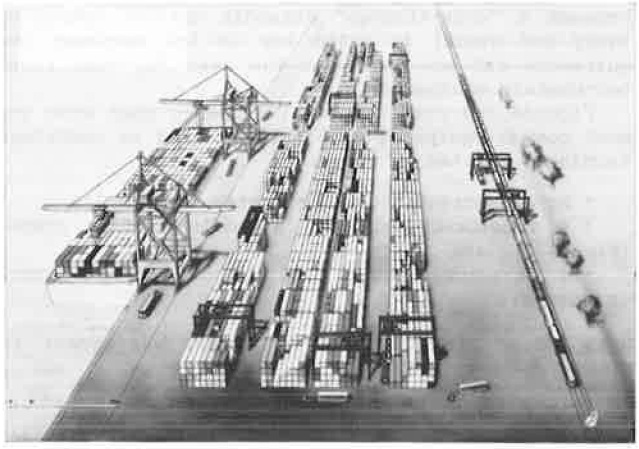

FIGURE 3 Model of tractor-chassis and rubber-tired gantry operation.

FIGURE 4 Shore-stack operation with straddle carriers in Hamburg.

FIGURE 5 Tractor-chassis and straddle carrier operation in Antwerp.

- Tractor-chassis and straddle carrier operation in use at the Ports of Antwerp and Bremen/Bremerhaven (Figure 5);
- Tractor-chassis and yard gantry operation in use at the Port of Hamburg (Figure 6); and
- Straddle carrier and rail-mounted gantry operation in use at the Port of Hamburg (Figure 7).

FIGURE 6 Tractor-chassis and rubber-tired gantry operation in Hamburg.

FIGURE 7 Straddle carrier transport and rail car loading with rail-mounted gantries in Hamburg.

CHOOSING BETWEEN GANTRY AND STRADDLE CARRIER

As far as a terminal operator making the choice between the straddle carrier and yard gantry-based systems is concerned, there is certainly no bias other than that of overall cost and operational style in the particular terminal situation. There is no single or ultimate rule that dictates a preference of one system over another. Equipment performance and reliability have reached high standards in both yard gantries and straddle carriers. Evaluations of the two for a particular application normally turn out to be quite close depending on the situation. The choice of equipment to be used is usually determined by

1. Cost factors
   - Cost of operation and maintenance of equipment (including labor),
   - Capital cost of land improvement as well as equipment, and
   - Cost of financing and available financing facilities.
2. Operational factors
   - Stacking requirements,
   - Flexibility requirements (including specific storage and loading requirements),
   - Local constraints (particularly the availability of space and the existing physical layout), and
   - Convenience and familiar practice.

Usually the following equipment cost considerations may shift the balance one way or another:

- Straddle carrier systems are lower in total capital investment, permit higher rates of depreciation for tax purposes, and tend to consume less fuel.
- Yard gantry systems are lower in overall cost of operation; the main reasons are the lower tire cost and the usually somewhat lower maintenance cost.

In addition to cost, operational features may be decisive, for example:

- Straddle carriers are more flexible in stacking and marshalling operations, even compared with relocatable rubber-tired gantries; straddle carriers are, in particular, the ideal equipment for fast random access, for prestacking of export containers on the quay, and for any quick action under unexpected circumstances;
- Yard gantries fulfill the lowest possible space requirement permitting narrow stack lanes and up to four-high stacks compared with a maximum of three-high stacks in the case of straddle carriers; and
- Yard gantries lend themselves to automatic operation with guidance systems and automatic positioning and integration into the electronic data transmission and control system of a yard (which may be an important feature for large and diversified container stacks).

Hence, studies to aid in choosing the equipment to be used usually have different results for different users and applications.

One additional point should be observed: both types of equipment are considered by today's technology standard to be reliable and economical. Formerly reported maintenance problems with straddle carriers have disappeared, particularly with the specific models and designs described in this paper. Functional downtime for both types of machines is down to less than 2 percent, sometime 1 percent, of scheduled operating time in yard operations that are well organized and provide good periodic preventive maintenance service. Repair parts and fuel consumption have been drastically reduced.

STACKING REQUIREMENTS AND YARD LAYOUT

Size, density, and accessibility of container stacks are the major parameters in equipment selection. The limit of stability for the height of free-standing stacks of loaded containers is considered to be four high. Yard gantries are normally designed for handling this height plus providing for one additional level for passing over four-high stacks with another container. Straddle carriers can normally lift containers three high, permitting two-high stacking plus a passing level, three-high stacking at the most. The horizontal stack arrangement will vary according to the type of handling equipment used.

With Straddle Carrier

The inside width of straddle carriers is matched to the container width. The chassis and the vertical columns of modern carriers are built extremely narrow and require a driving lane between container rows

only 1.2 to 1.5 m (4 to 5 ft) wide. A roadway with a width of approximately 20 m (66 ft) is required to provide for carrier access to the individual container stacks and as maneuvering space for entering the container rows, which are normally perpendicular to the roadway. These dimensions will normally suffice to determine the general space arrangement required in a terminal in order to provide the largest possible stacking density for transloading operations using straddle carriers.

With Yard Gantry Crane

If a decision has been made in favor of more dense stacking, however, yard gantries are typically used in lieu of the straddle carrier. Rail-mounted gantries (or bridge cranes) are applied as stationary equipment for width track gauges that may reach 50 m (165 ft) and span 15 container rows. The wide-track gantry, even though a high-capacity machine, does not offer the greatest flexibility of operation. Also, extremely wide stacks are not necessarily desirable for reasons of access. More often a stack width of five to seven container rows is sufficient or even preferred. In this case, rubber-tired stacking gantries provide a most efficient and quite flexible operational tool.

Rubber-tired wheels and a steering mechanism on yard gantry cranes permit longitudinal and lateral movement as well as slewing of the crane and thus assure full mobility for relocation within the yard. Moreover, the rail track is not necessary and there is no restriction of handling operations due to maintenance and repair work because the rubber-tired cranes can easily be maneuvered out of the work area. Allowing for a minimum spacing of 400 mm (16 in.) between the individual container rows and the required safety distance of at least 500 mm (20 in.) between the crane and a container, the resulting gantry track gauge is 23.3 m (76 ft) for six container rows or 26.1 m (86 ft) for seven container rows plus a truck lane. A spacing distance of 400 mm (16 in.) between containers is also recommended in the longitudinal direction of the container in order to provide sufficient space for the "flippers" of the spreader.

EQUIPMENT DESIGN CHARACTERISTICS

Spreader

Yard gantries as well as straddle carriers are normally equipped with telescopic spreaders adjustable for 20-, 30-, 35-, and 40-ft positions to match containers of International Standards Organization (ISO) or Sea-Land standards. Telescoping and twistlock actuation are normally hydraulically operated. Spreaders for straddle carriers and for yard gantries equipped with nonrotating trolleys normally permit a horizontal angular adjustment through the use of a shift mechanism. This permits the operator to place the spreader properly, even if a container is not perfectly aligned. Sensors, limit switches, and locking devices ensure reliable and safe spreader operation. Frequently flippers are used for guidance of the spreader onto the containers. Figure 8 shows a straddle carrier spreader.

Yard Gantry

The following equipment description refers to rubber-tired gantries. Rail-mounted gantries differ in the bogie system, which resembles that of other common rail-mounted cranes. Furthermore, the bridge girders of rail-mounted cranes are frequently cantilevered to one side, sometimes both, for easy truck or railway access. Rail-mounted cranes are generally electrically driven with power feed by cable.

FIGURE 8 Straddle carrier spreader.

The drive of a rubber-tired stacking crane may either be diesel-electric or diesel-hydraulic. In either case, it is independent of an external electric power supply. This factor contributes to the flexibility of these cranes.

In contrast with rail-mounted cranes, rubber-tired cranes must always be steered, even for straight travel. Slight alignment deviations in the wheels, tire pressure variations, an eccentric trolley position as well as side forces from trolley movement and wind generate sideward movements for which compensation must be made. Automatic steering of a rubber-tired crane along a wire loop is state of the art. The wire is laid in the driving lane. An alternating electric field with a frequency of 10 KHz, for instance, is produced in the wire. This alternating field induces an electric voltage in the sensors located on the crane, thus measuring the sideward deviation from the wire. The servohydraulic steering of the wheels is thereby controlled according to the sensor signals, providing for straight travel of the gantry.

Another method of steering is via differential motor speed control on both sides of the gantry. With this method of steering the different speeds of the drive motors produce a crabbing motion to compensate for crane tracking deviations. The differential steering is less accurate and more strenuous on the equipment than servohydraulic steering with pivoted wheels. Maneuvering is also more cumbersome and requires additional space. A sideward track correction first requires a crabbing motion, which, in turn, has to be corrected again.

To obtain the highest guidance accuracy, especially for automatic positioning of the crane, servohydraulic steering for track correction and crab angle compensation via motor speed control for crabbing compensation are combined. In this manner, accurate track travel and parallel gantry motion are both achieved. With a highly precise automatic steering system, a sideward offset tolerance of ±10 mm

(±3/8 in.) from the wire and a crab travel tolerance of ±20 mm (±3/4 in.) can be maintained.

Because of the sensitive mode of operation required in container handling, all drives of stacking cranes are generally equipped with variable speed DC motors. Controls may be of the Ward-Leonard or thyristor type according to a user's preference.

A crane's trolley can be either rigid or rotary. Trolley rotation is occasionally desirable in order to place containers, especially refrigerated containers, in a convenient position. Trolleys are mostly self-propelled with trolley-mounted hoisting gear. Small cranes may be designed with rope-pulled trolleys and stationary hoists in order to achieve lower equipment cost.

Wheel suspensions may be of the fork type with double-bearing axles, or single-bearing L-shaped axles can be used, permitting easy access to the wheels and facilitating wheel change.

Wheel arrangement is normally one per corner whenever wheel loads permit. For heavy cranes or where ground pressure restrictions prevail, arrangements with two wheels per corner (in line or in parallel) or even arrangements with four wheels per corner are chosen. Such a 16-wheeler gantry crane has two in-line sets of double wheels (four wheels) per corner. A standard wheel drive is by chain and sprocket and normally half the number of wheels are driven. In other cases, a drive by universal shaft is preferred, especially for double-wheel arrangements.

Some rubber-tired stacking cranes equipped with the various design features described are presented next.

Figure 9 shows a small crane with four wheels, a track gauge of 12.4 m (41 ft), and a fixed cabin. The stacking height capability is three containers, each with a height of up to 9 1/2 ft. The unit is

FIGURE 9 Small rubber-tired gantry crane.

used primarily for loading work. This type of work might also be handled by straddle carriers. A similar crane is shown in Figure 10. It has roughly the same dimensions; however, the operator's cabin is located at the trolley.

Both of the popular stacking cranes shown in Figure 11 have an inside straddle width of 22 m (72 ft) and can span six container rows and a truck lane. The height is designed to provide for stacking four containers plus the overhead passing level. In this

FIGURE 10 Rubber-tired gantry with cab at trolley.

FIGURE 11 Standard model rubber-tired gantry (six rows plus truck lane, four stacking plus one passing level).

picture the transversely positioned wheels at the left horizontal beam can easily be seen. This transverse position of individual wheels serves as an additional protective measure against wind forces when the crane is parked.

The stacking crane in Figure 12 straddles five

FIGURE 12 Rubber-tired gantry with rotary trolley.

FIGURE 13 Wheel arrangement—two wheels per corner.

container rows, stacked three levels high. It is equipped with a rotary trolley. The crane chassis has two wheels at each corner or a total of eight running wheels, two of which are driven wheels.

Figure 13 shows details of a crane chassis with single-bearing and cantilevered axles for the wheels that permit easy and rapid tire change. Also shown is the drive motor with the driveshaft running in an inclined position down to the wheel hub gear.

The crane shown in Figure 14 runs on 16 wheels and straddles seven rows of four-level container stacks as well as a truck lane. It is one of the two cranes (another will be added later in 1986) that are operating at the Hamburg Lager- und Speditions-gesellschaft (LSG) terminal. These cranes are among the largest rubber-tired cranes built up to this time for container handling. They are remarkable because of their size and especially with regard to

FIGURE 14 Large 16-wheel rubber-tired gantry (seven container rows plus truck lane, four plus one high).

the newly developed electronic system for automatic stacking and reclaiming with which they are equipped. This system is considered one of the most advanced automatic systems for electronic crane control. Job orders are sent directly from a stationary central computer to the crane's on-board computer by means of inductive data transfer. The crane operator merely controls the lower movement and the setting down of the spreader or container manually; all other movements and the crane positioning work are carried out automatically by the on-board computer.

The job orders coming to the crane from the central computer are stored temporarily in the on-board computer until ready for execution. As many as 170 orders can be stored. This offers the advantage that the crane can continue to work independently for several hours during any break in data transfer from the central computer.

Extremely accurate crane and trolley positioning is provided through a sensor and coding mark technique proven to be reliable in the adverse weather of Hamburg winters. Every container in a stack is provided an address that serves to identify a specific location in a preset sequence on a three-dimensional coordinate system. Incremental pulse transmitters report the actual value of the crane and trolley position to the on-board computer that guides the crane and the trolley into the position desired. While the crane and trolley are in movement the lifting gear is located in a safe upper-end position. This upper-end position depends on the stacking height of the container storage area and can be preset. The lifting movement also takes place automatically. This cycle begins on complete locking or unlocking of the twist locks of the spreader on a container.

Although this automated container-handling equipment represents an advance in crane technology, further development can be foreseen. Additional technical advances can be expected in the field of sensor technology and automatic identification systems.

Straddle Carrier

The straddle carrier, on the basis of the sheer number in use today, is probably the primary work horse of container ports. It is certainly considered the most versatile and flexible piece of equipment by many. It can perform all the functions of loading, stacking, and marshalling plus moving containers (Figures 15 and 16). The lifting capacity under the spreader of straddle carriers is normally 40 t. The typical maximum travel speed is 28 km/hr (17.4 mph) and the climbing capacity can be up to 17 percent grade. The newer T-type configuration has been most successful during the past 5 years. The advantage of a single-engine design is also a desirable feature.

Some of the unique design features of the T-design are to be found in the chassis, the wheel suspension, the brakes, the control system, and the drive (Figure 17). Contemporary design and component selection give the highest priority to savings in fuel consumption and ease of operation and maintenance. During practical operation of this modern equipment fuel savings of up to 15 percent over older machines have been attained. In our experience at Bremen/Bremerhaven, with an average of 4,000 operating hours per machine annually, a savings of 1/2 gal per hour or more than 2,000 gal per year has been found. Thus a carrier of this type has quite some economic leverage in a fleet of some 80 carriers.

Most of the improvement in fuel consumption has been achieved by developing a special fluid drive transmission with a torque converter connecting

FIGURE 15 Straddle carrier loading truck.

FIGURE 16 Straddle carrier loading rail car.

clutch that permits one to bypass the torque converter, thereby providing a direct mechanical connection between the engine and gear box during speed travel. An electronic control automatically switches over from fluid to mechanical transmission as soon as a prescribed engine speed is reached. Below that prescribed engine speed the transmission returns to fluid drive. The electronic control is programmed for optimum selection of the automatic gear shift and converter bypass thus providing an automatic system of transmission and a new form of "overdrive." It appears that this technology can only be used with straddle carriers that have a single-engine drive. Twin-engine straddle carriers require a differential function and, therefore, fluid transmissions on both sides of the vehicle. Slipping of wheels sometimes experienced in snow or icy conditions or on oily surfaces can be overcome by providing a locking device for the differential gear.

A typical eight-wheel carrier can be optionally equipped with two-wheel or four-wheel drive. A sturdy

FIGURE 17 Chassis and wheel suspension of straddle carrier.

mechanical dual drive train transmits the rotation from the engine platform to the wheels on either side of the vehicle via bevel gears and universal drive shafts. The entire "power package" of engine, transmission, hydraulic station, and electrical cabinets is centralized on the top platform allowing easy access for maintenance. The container-handling operation takes place at a safe distance below. Provisions are made to secure the lowest maintenance cost as well as to gain ease of access to components.

A modern hydraulic steering system permits sensitive steering control of all eight wheels. To protect the mechanical steering linkage, it is located under the chassis girder that is designed to be collision resistant and to stand up to the impacts and jolts encountered in daily operation. The telescopic wheel suspension uses long-life elastic blocs instead of springs or maintenance-prone hydraulic load distribution. Operating experience with elastic blocs has been excellent, and the system can be considered practically fail safe. Drum brakes have been replaced by disc brakes in the T-series carriers because of maintenance advantages, and the hydraulic dual circuit brake system also corresponds to more modern vehicle engineering practice.

Two horizontally arranged hydraulic hoisting cylinders can operate the hoisting chains for the cross beams and spreaders (Figure 18). The hydraulics can control a variable hoisting speed that may be dependent on the load being lifted. A hoisting speed of 17.5 m/min (57.4 ft/min) can be achieved thereby improving typical handling cycles. In this carrier the central hydraulic station is located on the top platform. It consists of compound pump sets driven by the main engine. Hoisting, steering, the two brake circuits, and the spreader functions are all actuated from the hydraulic station. Load-sensing devices control the pumping action of the hoist pumps, adjusting the hoisting speed to the load by control of pressure and flow rate.

A number of component options are typically available for the yard operator or designer to consider. A choice between two-wheel and four-wheel drive has been previously indicated. A wide range of engine selection is also available. The most standard engine provided in this carrier is a 10-cylinder, air-cooled diesel engine. Optional engines include various water-cooled makes; therefore, an operator's

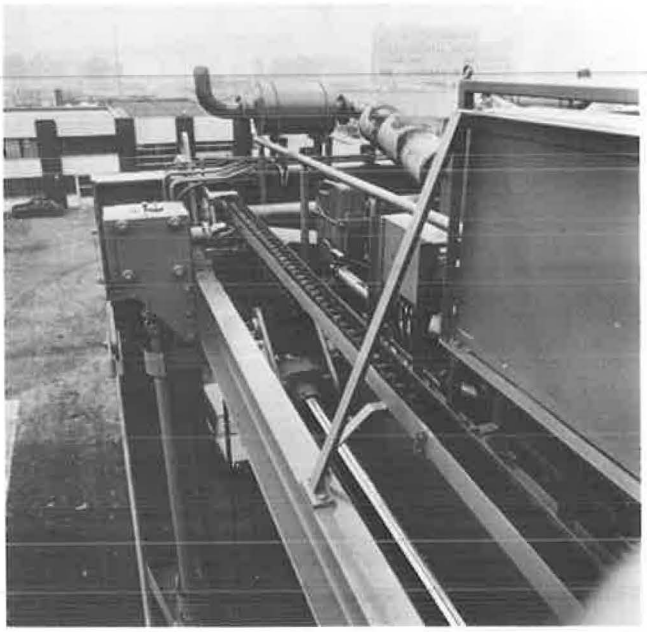

FIGURE 18 Hoisting arrangement.

FIGURE 20 Driver's seat and controls.

FIGURE 19 Engine platform with noise protection on engine.

preference concerning the engine and its make can normally be fulfilled. Tire sizes of 1400 and 1600 can be used with the carrier without requiring changes in the wheel forks. Although not normally required, the carrier engine can be noise protected to provide for extremely low noise levels (Figure 19). This noise supression may be needed if yard operations are in close proximity to residential areas.

There are several alternatives for locating the driver's cabin (Figure 20). Front or side cabins can typically be supplied. The cabin can also be equipped with two directional panels and two steering wheels. All cabins should provide excellent range of vision and be equipped with operator comfort accessories like heating and air conditioning.

Specific details of the design of a straddle carrier can contribute to ease of maintenance and safe operation. For example, where there are only 50 lubricating points the time expended on lubrication service can be restricted to only 1/2 shift. Ideally, lubrication intervals can be extended to 1,000 hr by using feeder reservoirs. Also, where hoisting cylinders are self-aligning through universal joint suspension, there is no difficulty in alignment following repair. The hoisting cylinder can be replaced without detachment of the hoisting chains. The hoisting chains themselves should feature shock absorbers and chain lubrication to extend their service life.

Maintenance cycles and availability of straddle carriers today reach the following performance levels:

- Annual number of operating hours: up to 6,000 hr per year,
- Maintenance check: not more than every 500 operating hours,
- Basic maintenance: not more than every 1,000 operating hours, and
- Extensive overhaul of the diesel engine and gears: not normally necessary until after 15,000 operating hours.

Experience with vehicle availability in Bremerhaven, for instance, has been that 95 percent can be attained (i.e., only 5 percent maintenance time). These figures can of course differ from facility to facility. The operational experience of the last 5 years has clearly shown that straddle carrier vehicles can be expected to attain service lives of 15 years or up to 90,000 operating hours. The straddle carrier of modern design is considered one of the most efficient and economical vehicles used in container transshipment operations worldwide, and the three-high design of the straddle carrier makes it able to cope with the height requirements of double-stack railway trains.

CONCLUSION

Straddle equipment--yard gantries or straddle carriers--is the name of the game in intermodalism whenever loading operations are combined with the requirement of maintaining container stacks and stack organization. In addition, the straddle carrier is a fast and flexible transport tool. The inevitable question of container-handling equipment system preference cannot be answered in general terms because individual conditions of operation and detailed cost-benefit analysis will determine the final choice.

The standards of equipment design, reliability, and maintenance characteristics have reached a high level and well-proven machinery is available. The choice of equipment may be difficult in some cases in which system investigations yield close cost-benefit results within the limits of accuracy available. The users, nevertheless, will certainly prefer the headache of making a sound equipment choice to the headaches they may have experienced with equipment reliability in previous times.