Material Transport Systems

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Material handling is defined by the Material Handling Industry of America\(^1\) as “the movement, storage, protection and control of materials throughout the manufacturing and distribution process including their consumption and disposal” [10]. The handling of materials must be performed safely, efficiently, at low cost, in a timely manner, accurately (the right materials in the right quantities to the right locations), and without damage to the materials. Material handling is an important yet often overlooked issue in production.

\(^1\)The Material Handling Industry of America (MHIA) is the trade association for material handling companies that do business in North America. The definition is published in their Annual Report each year [10].
The cost of material handling is a significant portion of total production cost, estimates averaging around 20–25% of total manufacturing labor cost in the United States [3]. The proportion of total cost varies, depending on the type of production and degree of automation in the material handling function.

In this part of the book, we discuss the material handling and identification systems used in production. The position of material handling in the larger production system is shown in Figure 10.1. In our coverage, we divide the subject into three major categories: (1) material transport systems, discussed in the present chapter, (2) storage systems, described in Chapter 11, and (3) automatic identification and tracking systems, presented in Chapter 12. In addition, several kinds of material handling devices are discussed in other chapters of the text, including industrial robots used for material handling (Chapter 8), pallet shuttles in NC machining centers (Chapter 14), conveyors in manual assembly lines (Chapter 15), transfer mechanisms in automated transfer lines (Chapter 16), and parts feeding devices in automated assembly (Chapter 17).

10.1 INTRODUCTION TO MATERIAL HANDLING

Material handling is an important activity within the larger system by which materials are moved, stored, and tracked in our commercial infrastructure. The term commonly used for the larger system is **logistics**, which is concerned with the acquisition, movement, storage, and distribution of materials and products, as well as the planning and control of these operations in order to satisfy customer demand. Logistics operations can be divided into two basic categories: external logistics and internal logistics. **External logistics** is concerned with transportation and related activities that occur outside of a facility. In general, these activities involve the movement of materials between different geographical locations. The five traditional modes of transportation are rail, truck, air, ship, and
pipeline. *Internal logistics,* more popularly known as material handling, involves the movement and storage of materials inside a given facility. Our interest in this book is on internal logistics. In this section, we first describe the various types of equipment used in material handling, and then identify some of the considerations required in the design of material handling systems.

### 10.1.1 Material Handling Equipment

A great variety of material handling equipment is available commercially. The equipment can be classified into four categories: (1) material transport equipment, (2) storage systems, (3) unitizing equipment, and (4) identification and tracking systems.

**Material Transport Equipment.** Material transport equipment is used to move materials inside a factory, warehouse, or other facility. The five main types of equipment are (1) industrial trucks, (2) automated guided vehicles, (3) rail-guided vehicles, (4) conveyors, and (5) hoists and cranes. These equipment types are described in Section 10.2.

**Storage Systems.** Although it is generally desirable to reduce the storage of materials in manufacturing, it seems unavoidable that raw materials and work-in-process will spend some time being stored, even if only temporarily. And finished products are likely to spend some time in a warehouse or distribution center before being delivered to the final customer. Accordingly, companies must give consideration to the most appropriate methods for storing materials and products prior to, during, and after manufacture. Storage methods and equipment can be classified into two major categories: (1) conventional storage methods and (2) automated storage systems. Conventional storage methods include bulk storage (storing items in an open floor area), rack systems, shelving and bins, and drawer storage. In general, conventional storage methods are labor intensive. Human workers put materials into storage and retrieve them from storage. Automated storage systems are designed to reduce or eliminate the manual labor involved in these functions. There are two major types of automated storage systems: (1) automated storage/retrieval systems and (2) carousel systems. These storage methods are described in greater detail in Chapter 11. In addition, mathematical models are developed to predict throughput and other performance characteristics of automated storage systems.

**Unitizing Equipment.** The term unitizing equipment refers to (1) containers used to hold individual items during handling and (2) equipment used to load and package the containers. Containers include pallets, boxes, baskets, barrels, pails, and drums, some of which are shown in Figure 10.2. Although seemingly mundane, containers are very important for moving materials efficiently as a unit load, rather than as individual items. Pallets and other containers that can be handled by forklift equipment are widely used in production and distribution operations. Most factories, warehouses, and distribution centers use forklift trucks to move unit loads on pallets. A given facility must often standardize on a specific type and size of container if it utilizes automatic transport and/or storage equipment to handle the loads.

The second category of unitizing equipment, loading and packaging equipment, includes *palletizers,* which are designed to automatically load cartons onto pallets and shrink-wrap plastic film around them for shipping, and *depalletizers,* which are designed to unload cartons from pallets. Other wrapping and packaging machines are also included in this equipment category.
Figure 10.2 Examples of unit load containers for material handling:
(a) wooden pallet, (b) pallet box, and (c) tote box.

Identification and Tracking Systems. Material handling must include a means of
keeping track of the materials being moved or stored. This is usually done by affixing
some kind of label to the item, carton, or unit load that uniquely identifies it. The most
common label used today is a bar code that can be read quickly and automatically by bar
code readers. This is the same basic technology used by grocery stores and retail mer-
chandisers. An alternative identification technology that is growing in importance is
RFID (for radio frequency identification). Bar codes, RFID, and other automatic identifi-
cation techniques are discussed in Chapter 12.

10.1.2 Design Considerations in Material Handling

Material handling equipment is usually assembled into a system. The system must be specified
and configured to satisfy the requirements of a particular application. Design of the system
depends on the materials to be handled, quantities and distances to be moved, type of production
facility served by the handling system, and other factors, including available budget. In this
section, we consider these factors that influence the design of the material handling system.

Material Characteristics. For handling purposes, materials can be classified by
the physical characteristics presented in Table 10.1, suggested by a classification scheme

<table>
<thead>
<tr>
<th>Category</th>
<th>Measures or Descriptors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical state</td>
<td>Solid, liquid, or gas</td>
</tr>
<tr>
<td>Size</td>
<td>Volume, length, width, height</td>
</tr>
<tr>
<td>Weight</td>
<td>Weight per piece, weight per unit volume</td>
</tr>
<tr>
<td>Shape</td>
<td>Long and flat, round, square, etc.</td>
</tr>
<tr>
<td>Condition</td>
<td>Hot, cold, wet, dirty, sticky</td>
</tr>
<tr>
<td>Risk of damage</td>
<td>Fragile, brittle, sturdy</td>
</tr>
<tr>
<td>Safety risk</td>
<td>Explosive, flammable, toxic, corrosive, etc.</td>
</tr>
</tbody>
</table>
of Muther and Haganas [16]. Design of the material handling system must take these factors into account. For example, if the material is a liquid and is to be moved in this state over long distances in great volumes, then a pipeline is the appropriate transport means. But this handling method would be infeasible for moving a liquid contained in barrels or other containers. Materials in a factory usually consist of solid items: raw materials, parts, and finished or semifinished products.

**Flow Rate, Routing, and Scheduling.** In addition to material characteristics, other factors must be considered in determining which type of equipment is most appropriate for the application. These other factors include (1) quantities and flow rates of materials to be moved, (2) routing factors, and (3) scheduling of the moves.

The amount or quantity of material to be moved affects the type of handling system that should be installed. If large quantities of material must be handled, then a dedicated handling system is appropriate. If the quantity of a particular material type is small but there are many different material types to be moved, then the handling system must be designed to be shared by the various materials moved. The amount of material moved must be considered in the context of time, that is, how much material is moved within a given time period. We refer to the amount of material moved per unit time as the **flow rate**. Depending on the form of the material, flow rate is measured in pieces/hr, pallet loads/hr, tons/hr, ft³/day, or similar units. Whether the material must be moved as individual units, in batches, or continuously has an effect on the selection of handling method.

Routing factors include pickup and drop-off locations, move distances, routing variations, and conditions that exist along the routes. Given that other factors remain constant, handling cost is directly related to the distance of the move: The longer the move distance, the greater the cost. Routing variations occur because different materials follow different flow patterns in the factory or warehouse. If these differences exist, the material handling system must be flexible enough to deal with them. Conditions along the route include floor surface condition, traffic congestion, whether a portion of the move is outdoors, whether the path is straight line or involves turns and changes in elevation, and the presence or absence of people along the path. All of these factors affect the design of the material transport system.

Scheduling relates to the timing of each individual delivery. In production as well as in many other material handling applications, the material must be picked up and delivered promptly to its proper destination to maintain peak performance and efficiency of the overall system. To the extent required by the application, the handling system must be responsive to this need for timely pickup and delivery of the items. Rush jobs increase material handling cost. Scheduling urgency is often mitigated by providing space for buffer stocks of materials at pickup and drop-off points. This allows a "float" of materials to exist in the system, thus reducing the pressure on the handling system for immediate response to a delivery request.

**Plant Layout.** Plant layout is an important factor in the design of a material handling system. When a new facility is being planned, the design of the handling system should be considered part of the layout. In this way, there is greater opportunity to create a layout that optimizes material flow in the building and utilizes the most appropriate type of handling system. In the case of an existing facility, there are more constraints on the design of the handling system. The present arrangement of departments and equipment in the building usually limits the attainment of optimum flow patterns.
The plant layout design should provide the following data for use in the design of the handling system: total area of the facility and areas within specific departments in the plant, relative locations of departments, arrangement of equipment in the layout, locations where materials must be picked up (load stations) and delivered (unload stations), possible routes between these locations, and distances traveled. Each of these factors affects flow patterns and selection of material handling equipment.

In Section 2.3, we described the conventional types of plant layout used in manufacturing: (1) process layout, (2) product layout, and (3) fixed-position layout. Different material handling systems are generally required for the three layout types. Table 10.2 summarizes the characteristics of the three conventional layout types and the kinds of material handling equipment usually associated with each layout type.

In process layouts, various different products are manufactured in small or medium batch sizes. The handling system must be flexible to deal with the variations. Considerable work-in-process is usually one of the characteristics of batch production, and the material handling system must be capable of accommodating this inventory. Hand trucks and fork-lift trucks (for moving pallet loads of parts) are commonly used in process layouts. Factory applications of automated guided vehicle systems are growing because they represent a versatile means of handling the different load configurations in medium and low volume production. Work-in-progress is often stored on the factory floor near the next scheduled machines. More systematic ways of managing in-process inventory include automated storage systems (Section 11.3).

A product layout involves production of a standard or nearly identical types of product in relatively high quantities. Final assembly plants for cars, trucks, and appliances are usually designed as product layouts. The transport system that moves the product is typically characterized as fixed route, mechanized, and capable of large flow rates. It sometimes serves as a storage area for work-in-process to reduce effects of downtime between production areas along the line of product flow. Conveyor systems are common in product layouts. Delivery of component parts to the various assembly workstations along the flow path is accomplished by trucks and similar unit load vehicles.

Finally, in a fixed-position layout, the product is large and heavy and therefore remains in a single location during most of its fabrication. Heavy components and sub-assemblies must be moved to the product. Handling systems used for these moves in fixed-position layouts are large and often mobile. Cranes, hoists, and trucks are common in this situation.

**Unit Load Principle.** The unit load principle stands as an important and widely applied principle in material handling. A unit load is simply the mass that is to be moved

<table>
<thead>
<tr>
<th>Layout Type</th>
<th>Characteristics</th>
<th>Typical Material Handling Equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process</td>
<td>Variations in product and processing, low and medium production rates</td>
<td>Hand trucks, forklift trucks, automated guided vehicle systems</td>
</tr>
<tr>
<td>Product</td>
<td>Limited product variety, high production rate</td>
<td>Conveyors for product flow, industrial trucks and automated guided vehicles to deliver components to stations</td>
</tr>
<tr>
<td>Fixed-position</td>
<td>Large product size, low production rate</td>
<td>Cranes, hoists, industrial trucks</td>
</tr>
</tbody>
</table>
TABLE 10.3 Standard Pallet Sizes Commonly Used in Factories and Warehouses

<table>
<thead>
<tr>
<th>Depth = x Dimension</th>
<th>Width = y Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>800 mm (32 in)</td>
<td>1000 mm (40 in)</td>
</tr>
<tr>
<td>900 mm (36 in)</td>
<td>1200 mm (48 in)</td>
</tr>
<tr>
<td>1000 mm (40 in)</td>
<td>1200 mm (48 in)</td>
</tr>
<tr>
<td>1060 mm (42 in)</td>
<td>1060 mm (42 in)</td>
</tr>
<tr>
<td>1200 mm (48 in)</td>
<td>1200 mm (48 in)</td>
</tr>
</tbody>
</table>

Sources: [6], [17].

or otherwise handled at one time. The unit load may consist of only one part, a container loaded with multiple parts, or a pallet loaded with multiple containers of parts. In general, the unit load should be designed to be as large as is practical for the material handling system that will move or store it, subject to considerations of safety, convenience, and access to the materials making up the unit load. This principle is widely applied in the truck, rail, and ship industries. Palletized unit loads are collected into truck loads, which then become larger unit loads themselves. Then these truck loads are aggregated once again on freight trains or ships, in effect becoming even larger unit loads.

There are good reasons for using unit loads in material handling, as described in Tompkins et al [17]: (1) multiple items can be handled simultaneously, (2) the required number of trips is reduced, (3) loading and unloading times are reduced, and (4) product damage is decreased. Using unit loads results in lower cost and higher operating efficiency.

Included in the definition of unit load is the container that holds or supports the materials to be moved. To the extent possible, these containers are standardized in size and configuration to be compatible with the material handling system. Examples of containers used to form unit loads in material handling are illustrated in Figure 10.2. Of the available containers, pallets are probably the most widely used, owing to their versatility, low cost, and compatibility with various types of material handling equipment. Most factories and warehouses use forklift trucks to move materials on pallets. Table 10.3 lists some of the most popular standard pallet sizes in use today. We use these standard pallet sizes in some of our analysis of automated storage/retrieval systems in Chapter 11.

10.2 MATERIAL TRANSPORT EQUIPMENT

In this section we examine the five categories of material transport equipment commonly used to move parts and other materials in manufacturing and warehouse facilities: (1) industrial trucks, manual and powered; (2) automated guided vehicles; (3) monorails and other rail-guided vehicles; (4) conveyors; and (5) cranes and hoists. Table 10.4 summarizes the principal features and kinds of applications for each equipment category. In Section 10.3, we consider quantitative techniques by which material transport systems consisting of this equipment can be analyzed.

10.2.1 Industrial Trucks

Industrial trucks are divided into two categories: nonpowered and powered. The nonpowered types are often referred to as hand trucks because they are pushed or pulled by human workers. Quantities of material moved and distances traveled are relatively low when this type of equipment is used to transport materials. Hand trucks are classified as
### TABLE 10.4 Summary of Features and Applications of Five Categories of Material Handling Equipment

<table>
<thead>
<tr>
<th>Material Handling Equipment</th>
<th>Features</th>
<th>Typical Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Industrial trucks, manual</td>
<td>Low cost</td>
<td>Moving light loads in a factory</td>
</tr>
<tr>
<td>Industrial trucks, powered</td>
<td>Low rate of deliveries/hour</td>
<td>Movement of pallet loads and palletized containers in a factory or warehouse</td>
</tr>
<tr>
<td>Automated guided vehicle systems</td>
<td>Medium cost</td>
<td>Moving pallet loads in factory or warehouse</td>
</tr>
<tr>
<td></td>
<td>High cost</td>
<td>Moving work-in-process along variable routes in low and medium production</td>
</tr>
<tr>
<td></td>
<td>Battery-powered vehicles</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Flexible routing</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Nonobstructive pathways</td>
<td></td>
</tr>
<tr>
<td>Monorails and other rail-guided vehicles</td>
<td>High cost</td>
<td>Moving single assemblies, products, or pallet loads along variable routes in factory or warehouse</td>
</tr>
<tr>
<td></td>
<td>Flexible routing</td>
<td>Moving large quantities of items over fixed routes in a factory or warehouse</td>
</tr>
<tr>
<td></td>
<td>On-the-floor or overhead types</td>
<td></td>
</tr>
<tr>
<td>Conveyors, powered</td>
<td>Great variety of equipment</td>
<td>Moving products along a manual assembly line</td>
</tr>
<tr>
<td></td>
<td>In-floor, on-the-floor, or overhead</td>
<td>Sortation of items in a distribution center</td>
</tr>
<tr>
<td></td>
<td>Mechanical power to move loads resides in pathway</td>
<td></td>
</tr>
<tr>
<td>Cranes and hoists</td>
<td>Lift capacities of more than 100 tons</td>
<td>Moving large, heavy items in factories, mills, warehouses, etc.</td>
</tr>
</tbody>
</table>

either two-wheel or multiple-wheel. Two-wheel hand trucks, Figure 10.3(a), are generally easier to manipulate by the worker but are limited to lighter loads. Multiple-wheeled hand trucks are available in several types and sizes. Two common types are dollies and pallet trucks. Dollies are simple frames or platforms as shown in Figure 10.3(b). Various wheel configurations are possible, including fixed wheels and caster-type wheels. Pallet trucks, shown in Figure 10.3(c), have two forks that can be inserted through the openings in a pallet.

![Figure 10.3 Examples of nonpowered industrial trucks (hand trucks): (a) two-wheel hand truck, (b) four-wheel dolly, and (c) hand-operated low-lift pallet truck.](image-url)
A lift mechanism is actuated by the worker to lift and lower the pallet off the ground using small diameter wheels near the end of the forks. In operation, the worker inserts the forks into the pallet, elevates the load, pulls the truck to its destination, lowers the pallet, and removes the forks.

Powered trucks are self-propelled to relieve the worker of having to move the truck manually. Three common types are used in factories and warehouses: (a) walkie trucks, (b) forklift rider trucks, and (c) towing tractors. Walkie trucks, Figure 10.4(a), are battery-powered vehicles equipped with wheeled forks for insertion into pallet openings but with no provision for a worker to ride on the vehicle. The truck is steered by a worker using a control handle at the front of the vehicle. The forward speed of a walkie truck is limited to around 3 mi/hr (5 km/hr), about the normal walking speed of a human.

Forklift rider trucks, Figure 10.4(b), are distinguished from walkie trucks by the presence of a modest cab for the worker to sit in and drive the vehicle. Forklift trucks range in load carrying capacity from about 450 kg (1,000 lb) up to more than 4,500 kg (10,000 lb). Forklift trucks have been modified to suit various applications. Some trucks have high reach capacities for accessing pallet loads on high rack systems, while others are capable of operating in the narrow aisles of high-density storage racks. Power sources for forklift trucks are either internal combustion engines (gasoline, liquefied petroleum gas, or compressed natural gas) or electric motors (using on-board batteries).

![Diagram of material transport equipment]

**Figure 10.4** Three principal types of powered trucks: (a) walkie truck, (b) forklift truck, and (c) towing tractor.
Industrial towing tractors, Figure 10.4(c), are designed to pull one or more trailing carts over the relatively smooth surfaces found in factories and warehouses. They are generally used for moving large amounts of materials between major collection and distribution areas. The runs between origination and destination points are usually fairly long. Power is supplied either by electrical motor (battery-powered) or internal combustion engine. Tow tractors also find significant applications in air transport operations for moving baggage and air freight in airports.

### 10.2.2 Automated Guided Vehicles

An *automated guided vehicle system* (AGVS) is a material handling system that uses independently operated, self-propelled vehicles guided along defined pathways. The vehicles are powered by on-board batteries that allow many hours of operation (8–16 hr is typical) before needing to be recharged. A distinguishing feature of an AGVS, compared to rail-guided vehicle systems and most conveyor systems, is that the pathways are unobtrusive. An AGVS is appropriate where different materials are moved from various load points to various unload points. An AGVS is therefore suitable for automating material handling in batch production and mixed model production.

**Types of Vehicles.** Automated guided vehicles can be divided into the following three categories: (1) driverless trains, (2) pallet trucks, and (3) unit load carriers, illustrated in Figure 10.5. A driverless train consists of a towing vehicle (the AGV) pulling one or

![Diagram of automated guided vehicles](image-url)

**Figure 10.5** Three types of automated guided vehicles: (a) driverless automated guided train, (b) AGV pallet truck, and (c) unit load carrier.
more trailers to form a train, as in Figure 10.5(a). It was the first type of AGVS to be introduced and is still widely used today. A common application is moving heavy payloads over long distances in warehouses or factories with or without intermediate pickup and drop-off points along the route. For trains consisting of five to ten trailers, this is an efficient transport system.

Automated guided pallet trucks, Figure 10.5(b), are used to move palletized loads along predetermined routes. In the typical application the vehicle is backed into the loaded pallet by a human worker who steers the truck and uses its forks to elevate the load slightly. Then the worker drives the pallet truck to the guidepath and programs its destination, and the vehicle proceeds automatically to the destination for unloading. The capacity of an AGVS pallet truck ranges up to several thousand kilograms, and some trucks are capable of handling two pallets rather than one. A more recent introduction related to the pallet truck is the forklift AGV. This vehicle can achieve significant vertical movement of its forks to reach loads on racks and shelves.

AGV unit load carriers are used to move unit loads from one station to another. They are often equipped for automatic loading and unloading of pallets or tote pans by means of powered rollers, moving belts, mechanized lift platforms, or other devices built into the vehicle deck. A typical unit load AGV is illustrated in Figure 10.5(c). Variations of unit load carriers include light load AGVs and assembly line AGVs. The light load AGV is a relatively small vehicle with corresponding light load capacity (typically 250 kg or less). It does not require the same large aisle width as a conventional AGV. Light load guided vehicles are designed to move small loads (single parts, small baskets, or tote pans of parts) through plants of limited size engaged in light manufacturing. An assembly line AGV is designed to carry a partially completed subassembly through a sequence of assembly workstations to build the product.

AGVS Applications. Automated guided vehicle systems are used in a growing number and variety of applications. The applications tend to correlate with the vehicle types previously described. The principal AGVS applications in production and logistics are (1) driverless train operations, (2) storage and distribution, (3) assembly line applications, and (4) flexible manufacturing systems. We have already described driverless train operations, which involve the movement of large quantities of material over relatively long distances.

A second application is storage and distribution operations. Unit load carriers and pallet trucks are typically used in these applications, which involve movement of material in unit loads. The applications often interface the AGVS with other automated handling or storage system, such as an automated storage/retrieval system (AS/RS) in a distribution center. The AGVS delivers incoming unit loads contained on pallets from the receiving dock to the AS/RS, which places the items into storage, and the AS/RS retrieves individual pallet loads from storage and transfers them to vehicles for delivery to the shipping dock. Storage/distribution operations also include light manufacturing and assembly plants in which work-in-process is stored in a central storage area and distributed to individual workstations for processing. Electronics assembly is an example of these kinds of applications. Components are “kitted” at the storage area and delivered in tote pans or trays to the assembly workstations in the plant. Light load AGVs are the appropriate vehicles in these applications.

AGV systems are used in assembly line applications, based on a trend that began in Europe. Unit load carriers and light load guided vehicles are used in these lines. In the usual
application, the production rate is relatively low (the product spending perhaps 4–10 min per station), and there are several different product models made on the line, each requiring a different processing time. Workstations are generally arranged in parallel to allow the line to deal with differences in assembly cycle time for different products. Between stations, components are kitted and placed on the vehicle for the assembly operations to be performed at the next station. The assembly tasks are usually performed with the work unit onboard the vehicle, thus avoiding the extra time required for unloading and reloading.

Another application area for AGVS technology is flexible manufacturing systems (FMSs, Chapter 19). In the typical operation, starting workparts are placed onto pallet fixtures by human workers in a staging area, and the AGVs deliver the parts to the individual workstations in the system. When the AGV arrives at the assigned station, the pallet is transferred from the vehicle platform to the station (such as the worktable of a machine tool) for processing. At the completion of processing, a vehicle returns to pick up the work and transport it to the next assigned station. An AGVS provides a versatile material handling system to complement the flexibility of the FMS.

AGVS technology is still developing, and the industry is continually working to design new systems to respond to new application requirements. An interesting example that combines two technologies involves the use of a robotic manipulator mounted on an automated guided vehicle to provide a mobile robot for performing complex handling tasks at various locations in a plant.

**Vehicle Guidance Technology.** The guidance system is the method by which AGVS pathways are defined and vehicles are controlled to follow the pathways. In this section, we discuss three technologies that are used in commercial systems for vehicle guidance: (1) imbedded guide wires, (2) paint strips, and (3) self-guided vehicles.

In the imbedded guide wire method, electrical wires are placed in a small channel cut into the surface of the floor. The channel is typically 3–12 mm (1/8–1/2 in) wide and 13–26 mm (1/2–1.0 in) deep. After the guide wire is installed, the channel is filled with cement to eliminate the discontinuity in the floor surface. The guide wire is connected to a frequency generator, which emits a low-voltage, low-current signal with a frequency in the range 1–15 kHz. This induces a magnetic field along the pathway that can be followed by sensors on board each vehicle. The operation of a typical system is illustrated in Figure 10.6. Two sensors (coils)

![Figure 10.6 Operation of the on-board sensor system that uses two coils to track the magnetic field in the guide wire.](image-url)
are mounted on the vehicle on either side of the guide wire. When the vehicle is located such that the guide wire is directly between the two coils, the intensity of the magnetic field measured by each coil is equal. If the vehicle strays to one side or the other, or if the guide wire path changes direction, the magnetic field intensity at the two sensors will become unequal. This difference is used to control the steering motor, which makes the required changes in vehicle direction to equalize the two sensor signals, thereby tracking the guide wire.

A typical AGVS layout contains multiple loops, branches, side tracks, and spurs, as well as pickup and drop-off stations. The most appropriate route must be selected from the alternative pathways available to a vehicle as it moves to a specified destination in the system. When a vehicle approaches a branching point where the guide path forks into two (or more) pathways, the vehicle must have a means of deciding which path to take. The two principal methods of making this decision in commercial wire guided systems are (1) the frequency select method and (2) the path switch select method. In the frequency select method, the guide wires leading into the two separate paths at the switch have different frequencies. As the vehicle enters the switch, it reads an identification code on the floor to determine its location. Depending on its programmed destination, the vehicle selects the correct guidepath by following only one of the frequencies. This method requires a separate frequency generator for each different frequency used in the guidepath layout.

The path switch select method operates with a single frequency throughout the guidepath layout. To control the path of a vehicle at a switch, the power is turned off in all other branches except the one that the vehicle is to travel on. To accomplish routing by the path switch select method, the guidepath layout is divided into blocks that are electrically insulated from each other. The blocks can be turned on and off either by the vehicles themselves or by a central control computer.

When paint strips are used to define the pathway, the vehicle uses an optical sensor system capable of tracking the paint. The strips can be taped, sprayed, or painted on the floor. One system uses a 1-in-wide paint strip containing fluorescent particles that reflect an ultraviolet (UV) light source from the vehicle. An on-board sensor detects the reflected light in the strip and controls the steering mechanism to follow it. Paint strip guidance is useful in environments where electrical noise renders the guide wire system unreliable or when the installation of guide wires in the floor surface is not practical. One problem with this guidance method is that the paint strip deteriorates with time. It must be kept clean and periodically replaced.

Self-guided vehicles (SGVs) represent the latest AGVS guidance technology. Unlike the previous two guidance methods, SGVs operate without continuously defined pathways. Instead, they use a combination of dead reckoning and beacons located throughout the plant that can be identified by on-board sensors. Dead reckoning refers to the capability of a vehicle to follow a given route in the absence of a defined pathway in the floor. Movement of the vehicle along the route is accomplished by computing the required number of wheel rotations in a sequence of specified steering angles. The computations are performed by the vehicle's on-board computer. As one would expect, positioning accuracy of dead reckoning decreases over long distances. Accordingly, the location of the self-guided vehicle must be periodically verified by comparing the calculated position with one or more known positions. These known positions are established using beacons located strategically throughout the plant. There are various types of beacons used in commercial SGV systems. One system uses bar-coded beacons mounted along the aisles. These beacons can be sensed by a rotating laser scanner on the vehicle. Based on the positions of the beacons, the on-board navigation computer uses triangulation
to update the positions calculated by dead reckoning. Another guidance system uses magnetic beacons imbedded in the plant floor along the pathway. Dead reckoning is used to move the vehicle between beacons, and the actual locations of the beacons provide data to update the computer's dead reckoning map.

It should be noted that dead reckoning can be used by AGV systems that are normally guided by in-floor guide wires or paint strips. This capability allows the vehicle to cross steel plates in the factory floor where guide wires cannot be installed or to depart from the guidepath for positioning at a load/unload station. At the completion of the dead reckoning maneuver, the vehicle is programmed to return to the guidepath to resume normal guidance control.

The advantage of self-guided vehicle technology over fixed pathways (guide wires and paint strips) is its flexibility. The SGV pathways are defined in software. The path network can be changed by entering the required data into the navigation computer. New docking points can be defined. The pathway network can be expanded by installing new beacons. These changes can be made quickly and without major alterations to the plant facility.

**Vehicle Management.** For the AGVS to operate efficiently, the vehicles must be well managed. Delivery tasks must be allocated to vehicles to minimize waiting times at load/unload stations. Traffic congestion in the guidepath network must be minimized. In this discussion we consider two aspects of vehicle management: (1) traffic control and (2) vehicle dispatching.

The purpose of traffic control in an automated guided vehicle system is to minimize interference between vehicles and to prevent collisions. Two methods of traffic control used in commercial AGV systems are (1) on-board vehicle sensing and (2) zone control. The two techniques are often used in combination. **On-board vehicle sensing,** also called **forward sensing,** uses one or more sensors on each vehicle to detect the presence of other vehicles and obstacles ahead on the guide path. Sensor technologies include optical and ultrasonic devices. When the on-board sensor detects an obstacle in front of it, the vehicle stops. When the obstacle is removed, the vehicle proceeds. If the sensor system is 100% effective, collisions between vehicles are avoided. The effectiveness of forward sensing is limited by the capability of the sensor to detect obstacles that are in front of it on the guide path. These systems are most effective on straight pathways. They are less effective at turns and convergence points where forward vehicles may not be directly in front of the sensor.

In **zone control,** the AGVS layout is divided into separate zones, and the operating rule is that no vehicle is permitted to enter a zone that is already occupied by another vehicle. The length of a zone is at least sufficient to hold one vehicle plus allowances for safety and other considerations. Other considerations include number of vehicles in the system, size and complexity of the layout, and the objective of minimizing the number of separate zones. For these reasons, the zones are normally much longer than a vehicle length. Zone control is illustrated in Figure 10.7 in its simplest form. When one vehicle occupies a given zone, any trailing vehicle is not allowed to enter that zone. The leading vehicle must proceed into the next zone before the trailing vehicle can occupy the current zone. When the forward movement of vehicles in the separate zones is controlled, collisions are prevented, and traffic in the overall system is controlled.

One means of implementing zone control is to use separate control units mounted along the guide path. When a vehicle enters a given zone, it activates the block in that zone to prevent any trailing vehicle from moving forward and colliding with the present
vehicle. As the present vehicle moves into the next (downstream) zone, it activates the block in that zone and deactivates the block in the previous zone. In effect, zones are turned on and off to control vehicle movement by the blocking system. Another method to implement zone control is to use a central computer, which monitors the location of each vehicle and attempts to optimize the movement of all vehicles in the system.

For an AGVS to serve its function, vehicles must be dispatched in a timely and efficient manner to the points in the system where they are needed. Several methods are used in AGV systems to dispatch vehicles: (1) on-board control panels, (2) remote call stations, and (3) central computer control. These dispatching methods are generally used in combination to maximize responsiveness and efficiency.

Each guided vehicle is equipped with some form of on-board control panel for the purpose of manual vehicle control, vehicle programming, and other functions. Most commercial vehicles can be dispatched by means of this control panel to a given station in the AGVS layout. Dispatching with an on-board control panel represents the lowest level of sophistication among the possible methods. It provides the AGVS with flexibility and timeliness in coping with changes and variations in delivery requirements.

Remote call stations represent another method for an AGVS to satisfy delivery requirements. The simplest call station is a push-button mounted at the load/unload station. This transmits a hailing signal for any available vehicle in the neighborhood to dock at the station and either pick up or drop off a load. The on-board control panel might then be used to dispatch the vehicle to the desired destination point. More sophisticated remote call stations permit the vehicle’s destination to be programmed at the same time the vehicle is called. This is a more automated dispatching method that is useful in AGV systems capable of automatic loading and unloading operations.

In a large factory or warehouse involving a high degree of automation, the AGVS servicing the facility must also be highly automated to achieve efficient operation of the entire production-storage-handling system. Central computer control is used to accomplish automatic dispatching of vehicles according to a preplanned schedule of pickups and deliveries in the layout and/or in response to calls from the various load/unload stations. In this dispatching method, the central computer issues commands to the vehicles in the system concerning their destinations and the operations they must perform. To accomplish the dispatching function, the central computer must possess current information on the location of each vehicle in the system so that it can make appropriate decisions about which vehicles to dispatch to what locations. Hence, the vehicles must continually communicate their whereabouts to the central controller. Radio frequency (RF) is commonly used to achieve the required communication links.
Vehicle Safety. The safety of humans located along the pathway is an important objective in AGVS design. An inherent safety feature of an AGV is that its traveling speed is slower than the normal walking pace of a human. This minimizes the danger that it will overtake a human walking along the path in front of the vehicle.

In addition, AGVs are usually provided with several other features specifically for safety reasons. A safety feature included in most guidance systems is automatic stopping of the vehicle if it strays more than a short distance, typically 50–150 mm (2–6 in), from the guidepath; the distance is referred to as the vehicle’s acquisition distance. This automatic stopping feature prevents a vehicle from running wild in the building. Alternatively, in the event that the vehicle is off the guidepath (e.g., for loading), its sensor system is capable of locking onto the guidepath when the vehicle is moved to within the acquisition distance.

Another safety device is an obstacle detection sensor located on each vehicle. This is the same on-board sensor used for traffic control. The sensor can detect obstacles along the path ahead, including humans. The vehicles are programmed either to stop when an obstacle is sensed ahead or to slow down. The reason for slowing down is that the sensed object may be located off to the side of the vehicle path or directly ahead but beyond a turn in the guide path, or the obstacle may be a person who will move out of the way as the AGV approaches. In any of these cases, the vehicle is permitted to proceed at a slower (safer) speed until it has passed the obstacle. The disadvantage of programming a vehicle to stop when it encounters an obstacle is that this delays the delivery and degrades system performance.

A safety device included on virtually all commercial AGVs is an emergency bumper. The bumpers are prominent in the illustrations shown in Figure 10.5. The bumper surrounds the front of the vehicle and protrudes ahead of it by a distance of 300 mm (12 in) or more. When the bumper makes contact with an object, the vehicle is programmed to brake immediately. Depending on the speed of the vehicle, its load, and other conditions, the distance the vehicle needs to come to a complete stop will vary from several inches to several feet. Most vehicles are programmed to require manual restarting after an obstacle has been encountered by the emergency bumper. Other safety devices on a typical vehicle include warning lights (blinking or rotating lights) and/or warning bells, which alert humans that the vehicle is present.

10.2.3 Monorails and Other Rail-Guided Vehicles

The third category of material transport equipment consists of motorized vehicles that are guided by a fixed rail system. The rail system consists of either one rail (called a monorail) or two parallel rails. Monorails in factories and warehouses are typically suspended overhead from the ceiling. In rail-guided vehicle systems using parallel fixed rails, the tracks generally protrude up from the floor. In either case, the presence of a fixed rail pathway distinguishes these systems from automated guided vehicle systems. As with AGVs, the vehicles operate asynchronously and are driven by an on-board electric motor. But unlike AGVs, which are powered by their own on-board batteries, rail guided vehicles pick up electrical power from an electrified rail (similar to an urban rapid transit rail system). This relieves the vehicle from periodic recharging of its battery; however, the electrified rail system introduces a safety hazard not present in an AGVS.

Routing variations are possible in rail-guided vehicle systems through the use of switches, turntables, and other specialized track sections. This permits different loads to
travel different routes, similar to an AGVS. Rail-guided systems are generally considered
to be more versatile than conveyor systems but less versatile than automated guided
vehicle systems. One of the original applications of nonpowered monorails was in the
meat processing industry before 1900. The slaughtered animals were hung from meat
hooks attached to overhead monorail trolleys. The trolleys were moved through the dif-
ferent departments of the plant manually by the workers. It is likely that Henry Ford got
the idea for the assembly line from observing these meat packing operations. Today, the
automotive industry makes considerable use of electrified overhead monorails to move
large components and subassemblies in its manufacturing operations.

10.2.4 Conveyors

A conveyor is a mechanical apparatus for moving items or bulk materials, usually inside
a facility. Conveyors are used when material must be moved in relatively large quantities
between specific locations over a fixed path, which may be in the floor, above the floor,
or overhead. Conveyors are either powered or nonpowered. In powered conveyors, the
power mechanism is contained in the fixed path, using chains, belts, rotating rolls, or
other devices to propel loads along the path. Powered conveyors are commonly used in
automated material transport systems in manufacturing plants, warehouses, and distri-
bution centers. In nonpowered conveyors, materials are moved either manually by human
workers who push the loads along the fixed path or by gravity from one elevation to a
lower elevation.

Types of Conveyors. A variety of conveyor equipment is commercially available.
Our primary interest here is in powered conveyors. Most of the major types of powered
conveyors, organized according to the type of mechanical power provided in the fixed
path, are briefly described in the following:

- Roller conveyors. In roller conveyors, the pathway consists of a series of tubes
  (rollers) that are perpendicular to the direction of travel, as in Figure 10.8(a). Loads
must possess a flat bottom surface of sufficient area to span several adjacent rollers.
Pallets, tote pans, or cartons serve this purpose well. The rollers are contained in a
fixed frame that elevates the pathway above floor level from several inches to sev-
eral feet. The loads are moved forward as the rollers rotate. Roller conveyors can
either be powered or nonpowered. Powered roller conveyors are driven by belts or
chains. Nonpowered roller conveyors are often driven by gravity so that the path-
way has a downward slope sufficient to overcome rolling friction. Roller conveyors
are used in a wide variety of applications, including manufacturing, assembly, pack-
aging, sortation, and distribution.

- Skate-wheel conveyors. These are similar in operation to roller conveyors. Instead of
  rollers, they use skate wheels rotating on shafts connected to a frame to roll pallets,
tote pans, or other containers along the pathway, as in Figure 10.8(b). Skate-wheel
conveyors are lighter in weight than roller conveyors. Applications of skate-wheel
conveyors are similar to those of roller conveyors, except that the loads must gener-
ally be lighter since the contacts between the loads and the conveyor are much more
concentrated. Because of their light weight, skate-wheel conveyors are sometimes
built as portable units that can be used for loading and unloading truck trailers at
shipping and receiving docks at factories and warehouses.
Figure 10.8 (a) Roller conveyor, (b) skate-wheel conveyor, (c) belt (flat) conveyor (support frame not shown), (d) in-floor towline conveyor, and (e) overhead trolley conveyor.

- **Belt Conveyors.** Belt conveyors consist of a continuous loop. Half its length is used for delivering materials, and the other half is the return run, as in Figure 10.8(c). The belt is made of reinforced elastomer (rubber), so that it possesses high flexibility but low extensibility. At one end of the conveyor is a drive roll that powers the belt. The flexible belt is supported by a frame that has rollers or support sliders along its forward loop. Belt conveyors are available in two common forms: (1) flat belts for pallets, individual parts, or even certain types of bulk materials; and (2) troughed belts for bulk materials. Materials placed on the belt surface travel along the moving pathway. In the case of troughed belt conveyors, the rollers and supports give the flexible belt a V shape on the forward (delivery) loop to contain bulk materials such as coal, gravel, grain, or similar particulate materials.

- **Chain conveyors.** The typical equipment in this category consists of chain loops in an over-and-under configuration around powered sprockets at the ends of the pathway. The conveyor may consist of one or more chains operating in parallel. The chains travel along channels in the floor that provide support for the flexible chain sections. Either the chains slide along the channel or they ride on rollers in the channel. The loads are generally dragged along the pathway using bars that project up from the moving chain.
- **In-floor towline conveyor.** These conveyors use four-wheel carts powered by moving chains or cables located in trenches in the floor, as in Figure 10.8(d). The chain or cable is called a towline. Pathways for the conveyor system are defined by the trench and cable, and the cable is driven as a powered pulley system. It is possible to switch between powered pathways to achieve flexibility in routing. The carts use steel pins that project below floor level into the trench to engage the chain for towing. (Gripper devices are substituted for pins when cable is used as the pulley system, as in the San Francisco trolleys.) The pin can be pulled out of the chain (or the gripper releases the cable) to disengage the cart for loading, unloading, switching, accumulating parts, and manually pushing a cart off the main pathway. Towline conveyor systems are used in manufacturing plants and warehouses.

- **Overhead trolley conveyor.** A trolley in material handling is a wheeled carriage running on an overhead rail from which loads can be suspended. An overhead trolley conveyor, Figure 10.8(e), consists of multiple trolleys, usually equally spaced along a fixed track. The trolleys are connected together and moved along the track by means of a chain or cable that forms a complete loop. Suspended from the trolleys are hooks, baskets, or other receptacles to carry loads. The chain (or cable) is attached to a drive pulley that pulls the chain at a constant velocity. The conveyor path is determined by the configuration of the track system, which has turns and possible changes in elevation. Overhead trolley conveyors are often used in factories to move parts and assemblies between major production departments. They can be used for both delivery and storage.

- **Power-and-free overhead trolley conveyor.** This conveyor is similar to the overhead trolley conveyor, except that the trolleys can be disconnected from the drive chain, providing the conveyor with an asynchronous capability. This is usually accomplished by using two tracks, one just above the other. The upper track contains the continuously moving endless chain, and the trolleys that carry loads ride on the lower track. Each trolley includes a mechanism by which it can be connected to the drive chain and disconnected from it. When connected, the trolley is pulled along its track by the moving chain in the upper track. When disconnected, the trolley is idle.

- **Cart-on-track conveyor.** This equipment consists of individual carts riding on a track a few feet above floor level. The carts are driven by means of a rotating shaft, as illustrated in Figure 10.9. A drive wheel, attached to the bottom of the cart and set at an angle to the rotating tube, rests against it and drives the cart forward. The cart speed is controlled by regulating the angle of contact between the drive wheel and the spinning tube. When the axis of the drive wheel is 45°, the cart is propelled forward. When the axis of the drive wheel is parallel to the tube, the cart does not move. Thus, control of the drive wheel angle on the cart allows power-and-free operation of the conveyor. One of the advantages of cart-on-track systems relative to many other conveyors is that the carts can be positioned with high accuracy. This permits their use for positioning work during production. Applications of cart-on-track systems include robotic spot welding lines in automobile body plants and mechanical assembly systems.

- **Other Conveyor Types.** Other powered conveyors include vibration-based systems and vertical lift conveyors. Screw conveyors are powered versions of the Archimedes screw, the water-raising device devised in ancient times, consisting of a large screw inside a tube, turned by hand to pump water uphill for irrigation purposes. Vibration-based conveyors use a flat track connected to an electromagnet that
imparts an angular vibratory motion to the track to propel items in the desired direction. This same principle is used in vibratory bowl feeders to deliver components in automated assembly systems (Section 17.1.2). Vertical lift conveyors include a variety of mechanical elevators designed to provide vertical motion, such as between floors or to link floor-based conveyors with overhead conveyors. Other conveyor types include nonpowered chutes, ramps, and tubes, which are driven by gravity.

**Conveyor Operations and Features.** As indicated by our preceding discussion, conveyor equipment covers a wide variety of operations and features. Let us restrict our discussion here to powered conveyors. Conveyor systems divide into two basic types in terms of the characteristic motion of the materials moved by the system: (1) continuous and (2) asynchronous. Continuous motion conveyors move at a constant velocity \( v_c \) along the path. They include belt, roller, skate-wheel, and overhead trolley.

Asynchronous conveyors operate with a stop-and-go motion in which loads, usually contained in carriers (e.g., hooks, baskets, carts), move between stations and then stop and remain at the station until released. Asynchronous handling allows independent movement of each carrier in the system. Examples of this type include overhead power-and-free trolley, in-floor towline, and cart-on-track conveyors. Some roller and skate-wheel conveyors can also be operated asynchronously. Reasons for using asynchronous conveyors include (1) to accumulate loads, (2) to temporarily store items, (3) to allow for differences in production rates between adjacent processing areas, (4) to smooth production when
cycle times are variable at stations along the conveyor, and (5) to accommodate different conveyor speeds along the pathway.

Conveyors can also be classified as (1) single direction, (2) continuous loop, and (3) recirculating. In Section 10.3.2, we present equations and techniques with which to analyze these conveyor systems. Single direction conveyors are used to transport loads one way from origin point to destination point, as depicted in Figure 10.10(a). These systems are appropriate when there is no need to move loads in both directions or to return containers or carriers from the unloading stations back to the loading stations. Single direction powered conveyors include roller, skate-wheel, belt, and chain-in-floor types. In addition, all gravity conveyors operate in one direction.

Continuous loop conveyors form a complete circuit, as in Figure 10.10(b). An overhead trolley conveyor is an example of this conveyor type. However, any conveyor type can be configured as a loop, even those previously identified as single direction conveyors, simply by connecting several single direction conveyor sections into a closed loop. A continuous loop system allows materials to be moved between any two stations along the pathway. Continuous loop conveyors are used when loads are moved in carriers (e.g., hooks, baskets) between load and unload stations and the carriers are affixed to the conveyor loop. In this design, the empty carriers are automatically returned from the unload station back to the load station.

The preceding description of a continuous loop conveyor assumes that items loaded at the load station are unloaded at the unload station. There are no loads in the return loop; the purpose of the return loop is simply to send the empty carriers back for reloading. This method of operation overlooks an important opportunity offered by a closed-loop conveyor: to store as well as deliver items. Conveyor systems that allow parts or products to remain on the return loop for one or more revolutions are called recirculating conveyors. In providing a storage function, the conveyor system can be used to accumulate parts to smooth out effects of loading and unloading variations at stations in the conveyor. There are two problems that can plague the operation of a recirculating conveyor system. One is that there may be times during the operation of the conveyor that no empty carriers are immediately available at the loading station when needed. The other problem is that no loaded carriers are immediately available at the unloading station when needed.

![Figure 10.10](attachment:image.png)

**Figure 10.10** (a) Single direction conveyor and (b) continuous loop conveyor.
It is possible to construct branching and merging points into a conveyor track to permit different routing of different loads moving in the system. In nearly all conveyor systems, it is possible to build switches, shuttles, or other mechanisms to achieve these alternate routings. In some systems, a push-pull mechanism or lift-and-carry device is required to actively move the load from the current pathway onto the new pathway.

10.2.5 Cranes and Hoists

The fifth category of transport equipment in material handling is cranes and hoists. Cranes are used for horizontal movement of materials in a facility, and hoists are used for vertical lifting. A crane invariably includes a hoist; thus, the hoist component of the crane lifts the load, and the crane transports the load horizontally to the desired destination. This class of material handling equipment includes cranes capable of lifting and moving very heavy loads, in some cases over 100 tons.

A hoist is a mechanical device used to raise and lower loads. As seen in Figure 10.11, a hoist consists of one or more fixed pulleys, one or more moving pulleys, and a rope, cable, or chain strung between the pulleys. A hook or other means for attaching the load is connected to the moving pulley(s). The number of pulleys in the hoist determines its mechanical advantage, which is the ratio of the load weight to the driving force required to lift the weight. The mechanical advantage of the hoist in our illustration is 4.0. The driving force to operate the hoist is applied either manually or by electric or pneumatic motor.

Cranes include a variety of material handling equipment designed for lifting and moving heavy loads using one or more overhead beams for support. Principal types of cranes found in factories include (a) bridge cranes, (b) gantry cranes, and (c) jib cranes. In all three types, at least one hoist is mounted to a trolley that rides on the overhead beam.

![Figure 10.11](image_url)  
Figure 10.11 A hoist with a mechanical advantage of 4.0: (a) sketch of the hoist and (b) diagram to illustrate mechanical advantage.
of the crane. A bridge crane consists of one or two horizontal girders or beams suspended between fixed rails on either end which are connected to the structure of the building, as shown in Figure 10.12(a). The hoist trolley can be moved along the length of the bridge, and the bridge can be moved the length of the rails in the building. These two drive capabilities provide motion in the x- and y-axis of the building, and the hoist provides motion in the z-axis direction. Thus, the bridge crane achieves vertical lifting due to its hoist and horizontal movement due to its orthogonal rail system. Large bridge cranes have girders that span up to 36.5 m (120 ft) and are capable of carrying loads up to 90,000 kg (100 tons). Large bridge cranes are controlled by operators riding in cabs on the bridge. Applications include heavy machinery fabrication, steel and other metal mills, and power-generating stations.

A gantry crane is distinguished from a bridge crane by the presence of one or two vertical legs that support the horizontal bridge. As with the bridge crane, a gantry crane includes one or more hoists that accomplish vertical lifting. Gantry cranes are available in a variety of sizes and capacities, the largest possessing spans of about 46 m (150 ft) and load capacities of 136,000 kg (150 tons). A double gantry crane has two legs. A half gantry crane, Figure 10.12(b), has a single leg on one end of the bridge, and the other end is supported by a rail mounted on the wall or other structural member of a building. A cantilever gantry crane has a bridge that extends beyond the span created by the support legs.

A jib crane consists of a hoist supported on a horizontal beam that is cantilevered from a vertical column or wall support, as illustrated in Figure 10.12(c). The horizontal beam pivots about the vertical axis formed by the column or wall to provide a horizontal sweep for the crane. The beam also serves as the track for the hoist trolley to provide radial travel along the length of the beam. Thus, the horizontal area included by a jib crane is circular or semicircular. As with other cranes, the hoist provides vertical lift and lower motions. Standard capacities of jib cranes range up to about 5000 kg. Wall-mounted jib cranes can achieve a swing of about 180°, while a floor-mounted jib crane using a column or post as its vertical support can sweep a full 360°.

![Diagram of a bridge crane](image)

![Diagram of a gantry crane](image)

![Diagram of a jib crane](image)

**Figure 10.12** Three types of cranes: (a) bridge crane, (b) gantry crane (a half gantry crane is shown), and (c) jib crane.
10.3 ANALYSIS OF MATERIAL TRANSPORT SYSTEMS

Quantitative models are useful for analyzing material flow rates, delivery cycle times, and other aspects of system performance. The analysis may be useful in determining equipment requirements; for example, how many forklift trucks will be required to satisfy a given flow rate specification. Material transport systems can be classified as vehicle-based systems or conveyor systems. Our coverage of the quantitative models is organized along these lines.

10.3.1 Analysis of Vehicle-Based Systems

Equipment used in vehicle-based material transport systems includes industrial trucks (both hand trucks and powered trucks), automated guided vehicles, monorails and other rail-guided vehicles, and certain types of conveyor systems (e.g., in-floor towline conveyors). These systems are commonly used to deliver individual loads between several different origination and destination points. Two graphical tools that are useful for displaying and analyzing data in these deliveries are the from-to chart and the network diagram. The from-to chart is a table that can be used to indicate material flow data and distances between multiple locations. Table 10.5 illustrates a from-to chart that lists flow rates and distances between five workstations in a manufacturing system. The left-hand vertical column lists the origination points (loading stations), while the horizontal row at the top identifies the destination locations (unloading stations).

Network diagrams can also be used to indicate the same type of information. A network diagram consists of nodes and arrows, and the arrows indicate relationships among the nodes. In material handling, the nodes represent locations (e.g., load and unload stations), and the arrows represent material flows and/or distances between the stations. Figure 10.13 shows a network diagram that provides the same information as Table 10.5.

Mathematical equations can be developed to describe the operation of vehicle-based material transport systems. We assume that the vehicle operates at a constant velocity throughout its operation and ignore effects of acceleration, deceleration, and other speed differences that might depend on whether the vehicle is traveling loaded or empty. The time for a typical delivery cycle in the operation of a vehicle-based transport system consists of (1) loading at the pickup station, (2) travel time to the drop-off station, (3) unloading at the drop-off station, and (4) empty travel time of the vehicle between deliveries. The total cycle time per delivery per vehicle is given by

\[ T_c = T_L + \frac{T_d}{v_c} + T_U + \frac{T_e}{v_o} \]  

(10.1)

| TABLE 10.5 From-To Chart Showing Flow Rates, loads/hr (Value Before the Slash Mark) and Travel Distances, (Value After the Slash Mark) Between Stations in a Layout |
| --- | --- | --- | --- | --- | --- |
| From | To | 1 | 2 | 3 | 4 |
| 1 | 9/50 | 5/120 | 6/205 | 0 |
| 2 | 0 | 0 | 0 | 0 | 9/80 |
| 3 | 0 | 0 | 0 | 2/85 | 3/170 |
| 4 | 0 | 0 | 0 | 8/85 |
| 5 | 0 | 0 | 0 | 0 | 0 |
where $T_c = \text{delivery cycle time (min/del)}$, $T_{L} = \text{time to load at load station (min)}$, $L_d = \text{distance the vehicle travels between load and unload station (m, ft)}$, $v_c = \text{carrier velocity (m/min, ft/min)}$, $T_{U} = \text{time to unload at unload station (min)}$, and $L_e = \text{distance the vehicle travels empty until the start of the next delivery cycle (m, ft)}$.

The $T_c$ calculated by Eq. (10.1) must be considered an ideal value, because it ignores any time losses due to reliability problems, traffic congestion, and other factors that may slow down a delivery. In addition, not all delivery cycles are the same. Originations and destinations may be different from one delivery to the next, which will affect the $L_d$ and $L_e$ terms in the equation. Accordingly, these terms are considered to be average values for the population of loaded and empty distances traveled by the vehicle during the course of a shift or other period of analysis.

The delivery cycle time can be used to determine certain parameters of interest in the vehicle-based transport system. Let us make use of $T_c$ to determine two parameters: (1) rate of deliveries per vehicle and (2) number of vehicles required to satisfy a specified total delivery requirement. We will base our analysis on hourly rates and requirements; however, the equations can readily be adapted for other periods.

The hourly rate of deliveries per vehicle is 60 min divided by the delivery cycle time $T_c$, adjusting for any time losses during the hour. The possible time losses include (1) availability, (2) traffic congestion, and (3) efficiency of manual drivers in the case of manually operated trucks. Availability (symbolized $A$) is a reliability factor (Section 3.1.3) defined as the proportion of total shift time that the vehicle is operational and not broken down or being repaired.

To deal with the time losses due to traffic congestion, let us define the traffic factor $F_t$ as a parameter for estimating the effect of these losses on system performance. Sources of inefficiency accounted for by the traffic factor include waiting at intersections, blocking of vehicles (as in an AGVS), and waiting in a queue at load/unload stations. If these situations do not occur, then $F_t = 1.0$. As blocking increases, the value of $F_t$ decreases. Waiting at intersections, blocking, and waiting in line at load/unload stations are affected by the number of vehicles in the system relative to the size of the layout. If there is only one vehicle in the system, no blocking should occur, and the traffic factor will be 1.0. For systems with many vehicles, there will be more instances of blocking and congestion, and the traffic factor will take a lower value. Typical values of traffic factor for an AGVS range between 0.85 and 1.0 [4].
For systems based on industrial trucks, including both hand trucks and powered trucks that are operated by human workers, traffic congestion is probably not the main cause of low operating performance. Instead, performance depends primarily on the work efficiency of the operators who drive the trucks. Let us define worker efficiency here as the actual work rate of the human operator relative to work rate expected under standard or normal performance. Let \( E_w \) symbolize the worker efficiency.

With these factors defined, we can now express the available time per hour per vehicle as 60 min adjusted by \( A, F_t, \) and \( E_w \). That is,

\[
AT = 60AF_tE_w
\]

where \( AT \) = available time (min/hr per vehicle), \( A \) = availability, \( F_t \) = traffic factor, and \( E_w \) = worker efficiency. The parameters \( A, F_t, \) and \( E_w \) do not take into account poor vehicle routing, poor guideway layout, or poor management of the vehicles in the system. These factors should be minimized, but if present they are accounted for in the values of \( L_d \) and \( L_e \).

We can now write equations for the two performance parameters of interest. The rate of deliveries per vehicle is given by

\[
R_{dv} = \frac{AT}{T_c}
\]

where \( R_{dv} \) = hourly delivery rate per vehicle (del/hr per vehicle), \( T_c \) = delivery cycle time computed by Eq. (10.1) (min/del), and \( AT \) = the available time in 1 hr with adjustments for time losses (min/hr).

The total number of vehicles (trucks, AGVs, trolleys, carts, etc.) needed to satisfy a specified total delivery schedule \( R_f \) in the system can be estimated by first calculating the total workload required and then dividing by the available time per vehicle. Workload is defined as the total amount of work, expressed in terms of time, that must be accomplished by the material transport system in 1 hr. This can be expressed as

\[
WL = R_fT_c
\]

where \( WL \) = workload (min/hr), \( R_f \) = specified flow rate of total deliveries per hour for the system (del/hr), and \( T_c \) = delivery cycle time (min/del). Now the number of vehicles required to accomplish this workload can be written as

\[
n_c = \frac{WL}{AT}
\]

where \( n_c \) = number of carriers required, \( WL \) = workload (min/hr), and \( AT \) = available time per vehicle (min/hr per vehicle). Substituting Eqs. (10.3) and (10.4) into Eq. (10.5) provides an alternative way to determine

\[
n_c = \frac{R_f}{R_{dv}}
\]

where \( n_c \) = number of carriers required, \( R_f \) = total delivery requirements in the system (del/hr), and \( R_{dv} \) = delivery rate per vehicle (del/hr per vehicle). Although the traffic factor accounts for delays experienced by the vehicles, it does not include delays encountered by a load/unload station that must wait for the arrival of a vehicle. Because of the random nature of the load/unload demands, workstations are likely to experience waiting time while vehicles are busy with other deliveries. The preceding equations do not consider this idle time or its impact on operating cost. If station idle time is to be minimized, then more vehicles may
be needed than the number indicated by Eqs. (10.5) or (10.6). Mathematical models based on queueing theory are appropriate to analyze this more complex stochastic situation.

EXAMPLE 10.1 Determining Number of Vehicles in an AGVS

Consider the AGVS layout in Figure 10.14. Vehicles travel counterclockwise around the loop to deliver loads from the load station to the unload station. Loading time at the load station = 0.75 min, and unloading time at the unload station = 0.50 min. We are interested in determining how many vehicles are required to satisfy demand for this layout if a total of 40 del/hr must be completed by the AGVS. The following performance parameters are given: vehicle velocity = 50 m/min, availability = 0.95, traffic factor = 0.90, and operator efficiency does not apply, so $E_w = 1.0$. Determine (a) travel distances loaded and empty, (b) ideal delivery cycle time, and (c) number of vehicles required to satisfy the delivery demand.

**Solution:**  
(a) Ignoring effects of slightly shorter distances around the curves at corners of the loop, the values of $L_u$ and $L_e$ are readily determined from the layout to be 110 m and 80 m, respectively.  
(b) Ideal cycle time per delivery per vehicle is given by Eq. (10.1):

$$T_c = 0.75 + \frac{110}{50} + 0.50 + \frac{80}{50} = 5.05 \text{ min}$$

(c) To determine the number of vehicles required to make 40 del/hr, we compute the workload of the AGVS and the available time per hour per vehicle:

$$WL = 40(5.05) = 202 \text{ min/hr}$$

$$AT = 60(0.95)(0.90)(1.0) = 51.3 \text{ min/hr per vehicle}$$

![AGVS loop layout for Example 10.1.](image)

Key: Unld = unload, Man = manual operation, dimensions in meters (m).
Therefore, the number of vehicles required is
\[ n_v = \frac{202}{51.3} = 3.94 \text{ vehicles} \]
This value should be rounded up to \( n_v = 4 \) vehicles, since the number of vehicles must be an integer.

Determining the average travel distances, \( L_d \) and \( L_e \), requires analysis of the particular AGVS layout. For a simple loop layout such as in Figure 10.14, determining these values is straightforward. For a complex AGVS layout, the problem is more difficult. The following example illustrates the issue.

**EXAMPLE 10.2 Determining \( L_d \) for a More-Complex AGVS Layout**

The layout for this example is shown in Figure 10.15, and the from-to chart is presented in Table 10.5. The AGVS includes load station 1 where raw parts enter the system for delivery to any of three production stations 2, 3, and 4. Unload station 5 receives finished parts from the production stations. Load

![Figure 10.15 AGVS layout for production system of Example 10.2. Key: Proc = processing operation, Aut = automated, Unld = unload, Man = manual operation, dimensions in meters (m).](image-url)
and unload times at stations 1 and 5 are each 0.5 min. Production rates for each workstation are indicated by the delivery requirements in Table 10.5. A complicating factor is that some parts must be transshipped between stations 3 and 4. Vehicles move in the direction indicated by the arrows in the figure. Determine the average delivery distance, \( L_d \).

**Solution.** Table 10.5 shows the number of deliveries and corresponding distances between the stations. The distance values are taken from the layout drawing in Figure 10.15. To determine the value of \( L_d \), a weighted average must be calculated based on the number of trips and corresponding distances shown in the from-to chart for the problem:

\[
L_d = \frac{9(50) + 5(120) + 6(205) + 9(80) + 2(85) + 3(170) + 8(85)}{9 + 5 + 6 + 9 + 2 + 3 + 8} = \frac{4360}{42} = 103.8 \text{ m}
\]

Determining \( L_e \), the average distance a vehicle travels empty during a delivery cycle, is more complicated. It depends on the dispatching and scheduling methods used to decide how a vehicle should proceed from its last drop-off to its next pickup. In Figure 10.15, if each vehicle must travel back to station 1 after each drop-off at stations 2, 3, and 4, then the empty distance between pick-ups would be very long indeed. \( L_e \) would be greater than \( L_d \). On the other hand, if a vehicle could exchange a raw workpart for a finished part while stopped at a given workstation, then empty travel time for the vehicle would be minimized. However, this would require a two-position platform at each station to enable the exchange. So this issue must be considered in the initial design of the AGVS. Ideally, \( L_e \) should be reduced to zero. It is highly desirable to minimize the average distance a vehicle travels empty through good AGVS design and good scheduling of the vehicles. Our mathematical model of vehicle-based systems indicates that the delivery cycle time will be reduced if \( L_e \) is minimized, and this will have a beneficial effect on the vehicle delivery rate and the number of vehicles required to operate the system. Two of our exercise problems at the end of the chapter ask the reader to determine \( L_e \) under different operating scenarios.

### 10.3.2 Conveyor Analysis

Conveyor operations have been analyzed in the research literature (see references [8], [9], [12], [13], [14], and [15]). In our discussion here, we consider the three basic types of conveyor operations discussed in Section 10.2.4: (1) single direction conveyors, (2) continuous loop conveyors, and (3) recirculating conveyors.

**Single Direction Conveyors.** Consider the case of a single direction powered conveyor with one load station at the upstream end and one unload station at the downstream end, as in Figure 10.10(a). Materials are loaded at one end and unloaded at the other. The materials may be parts, cartons, pallet loads, or other unit loads. Assuming the conveyor operates at a constant speed, the time required to move materials from load station to unload station is given by

\[
T_d = \frac{L_d}{v_c}
\]  
(10.7)
where \( T_d \) = delivery time (min), \( L_d \) = length of conveyor between load and unload stations (m, ft), and \( v_c \) = conveyor velocity (m/min, ft/min).

The flow rate of materials on the conveyor is determined by the rate of loading at the load station. The loading rate is limited by the reciprocal of the time required to load the materials. Given the conveyor speed, the loading rate establishes the spacing of materials on the conveyor. Summarizing these relationships,

\[
R_f = R_L = \frac{v_c}{s_c} \leq \frac{1}{T_L}
\]

(10.8)

where \( R_f \) = material flow rate (parts/min), \( R_L \) = loading rate (parts/min), \( s_c \) = center-to-center spacing of materials on the conveyor (m/part, ft/part), and \( T_L \) = loading time (min/part). One might be tempted to think that the loading rate \( R_L \) is the reciprocal of the loading time \( T_L \). However, \( R_L \) is set by the flow rate requirement \( R_f \), while \( T_L \) is determined by ergonomic factors. The worker who loads the conveyor may be capable of performing the loading task at a rate that is faster than the required flow rate. On the other hand, the flow rate requirement cannot be set faster than it is humanly possible to perform the loading task.

An additional requirement for loading and unloading is that the time required to unload the conveyor must be equal to or less than the reciprocal of material flow rate. That is,

\[
T_U \leq \frac{1}{R_f}
\]

(10.9)

where \( T_U \) = unloading time (min/part). If unloading requires more time than the time interval between arriving loads, then loads may accumulate or be dumped onto the floor at the downstream end of the conveyor.

We are using parts as the material in Eqs. (10.8) and (10.9), but the relationships apply to other unit loads as well. The advantage of the unit load principle (Section 10.1.2) can be demonstrated by transporting \( n_p \) parts in a carrier rather than a single part. Recasting Eq. (10.8) to reflect this advantage, we have

\[
R_f = \frac{n_p v_c}{s_c} \leq \frac{1}{T_L}
\]

(10.10)

where \( R_f \) = flow rate (parts/min), \( n_p \) = number of parts per carrier, \( s_c \) = center-to-center spacing of carriers on the conveyor (m/carrier, ft/carrier), and \( T_L \) = loading time per carrier (min/carrier). The flow rate of parts transported by the conveyor is potentially much greater in this case. However, loading time is still a limitation, and \( T_L \) may consist of not only the time to load the carrier onto the conveyor but also the time to load parts into the carrier. The preceding equations must be interpreted and perhaps adjusted for the given application.

**EXAMPLE 10.3 Single Direction Conveyor**

A roller conveyor follows a pathway 35 m long between a parts production department and an assembly department. Velocity of the conveyor is 40 m/min. Parts are loaded into large tote pans, which are placed onto the conveyor at the load station in the production department. Two operators work the loading station. The first worker loads parts into tote pans, which takes 25 sec. Each tote pan holds 20 parts. Parts enter the loading station from production at a rate that is in balance with this 25-sec cycle. The second worker loads tote pans
onto the conveyor, which takes only 10 sec. Determine: (a) spacing between tote pans along the conveyor, (b) maximum possible flow rate in parts/min, and (c) the minimum time required to unload the tote pan in the assembly department.

**Solution:** (a) Spacing between tote pans on the conveyor is determined by the loading time. It takes only 10 sec to load a tote pan onto the conveyor, but 25 sec are required to load parts into the tote pan. Therefore, the loading cycle is limited by this 25 sec. At a conveyor speed of 40 m/min, the spacing will be

\[ s_c = \frac{25}{60 \text{ min}} \times 40 \text{ m/min} = 16.67 \text{ m} \]

(b) Flow rate is given by Eq. (10.10):

\[ R_f = \frac{20 \times 40}{16.67} = 48 \text{ parts/min} \]

This is consistent with the parts loading rate of 20 parts in 25 sec, which is 0.8 parts/sec or 48 parts/min.

(c) The minimum allowable time to unload a tote pan must be consistent with the flow rate of tote pans on the conveyor. This flow rate is one tote pan every 25 sec, so

\[ T_U \leq 25 \text{ sec} \]

**Continuous Loop Conveyors.** Consider a continuous loop conveyor such as an overhead trolley in which the pathway is formed by an endless chain moving in a track loop, and carriers are suspended from the track and pulled by the chain. The conveyor moves parts in the carriers between a load station and an unload station. The complete loop is divided into two sections: a delivery (forward) loop in which the carriers are loaded and a return loop in which the carriers travel empty, as shown in Figure 10.10(b). The length of the delivery loop is \( L_d \), and the length of the return loop is \( L_e \). Total length of the conveyor is therefore \( L = L_d + L_e \). The total time required to travel the complete loop is

\[ T_c = \frac{L}{v_c} \]  

(10.11)

where \( T_c \) = total cycle time (min), and \( v_c \) = speed of the conveyor chain (m/min, ft/min). The time a load spends in the forward loop is

\[ T_d = \frac{L_d}{v_c} \]  

(10.12)

where \( T_d \) = delivery time on the forward loop (min).

Carriers are equally spaced along the chain at a distance \( s_c \) apart. Thus, the total number of carriers in the loop is given by

\[ n_c = \frac{L}{s_c} \]  

(10.13)

where \( n_c \) = number of carriers, \( L \) = total length of the conveyor loop (m, ft), and \( s_c \) = center-to-center distance between carriers (m/carrier, ft/carrier). The value of \( n_c \) must be an integer, and so \( L \) and \( s_c \) must be consistent with that requirement.

Each carrier is capable of holding parts on the delivery loop, and it holds no parts on the return trip. Since only those carriers on the forward loop contain parts, the maximum number of parts in the system at any one time is given by
Total parts in system \[ \frac{n_p n_c L_d}{L} \] (10.14)

As in the single direction conveyor, the maximum flow rate between load and unload stations is

\[ \frac{n_p v_c}{s_c} \]

where \( R_f \) = parts per minute. Again, this rate must be consistent with limitations on the time it takes to load and unload the conveyor, as defined in Eqs. (10.8)-(10.10).

**Recirculating Conveyors.** Recall the two problems complicating the operation of a recirculating conveyor system (Section 10.2.4): (1) the possibility that no empty carriers are immediately available at the loading station when needed and (2) the possibility that no loaded carriers are immediately available at the unloading station when needed. The case of a recirculating conveyor with one load station and one unload station was analyzed by Kwo [8], [9]. According to his analysis, three basic principles must be obeyed in designing such a conveyor system:

1. **Speed Rule.** The operating speed of the conveyor must be within a certain range. The lower limit of the range is determined by the required loading and unloading rates at the respective stations. These rates are dictated by the external systems served by the conveyor. Let \( R_L \) and \( R_U \) represent the required loading and unloading rates at the two stations, respectively. Then the conveyor speed must satisfy the relationship

\[ \frac{n_p v_c}{s_c} \geq \text{Max} \{ R_L, R_U \} \] (10.15)

where \( R_L \) = required loading rate (parts/min), and \( R_U \) = the corresponding unloading rate. The upper speed limit is determined by the physical capabilities of the material handlers to perform the loading and unloading tasks. Their capabilities are defined by the time required to load and unload the carriers, so that

\[ \frac{v_c}{s_c} \leq \text{Min} \left\{ \frac{1}{T_L}, \frac{1}{T_U} \right\} \] (10.16)

where \( T_L \) = time required to load a carrier (min/carrier), and \( T_U \) = time required to unload a carrier. In addition to Eqs. (10.15) and (10.16), another limitation is of course that the speed must not exceed the physical limits of the mechanical conveyor itself.

2. **Capacity Constraint.** The flow rate capacity of the conveyor system must be at least equal to the flow rate requirement to accommodate reserve stock and allow for the time elapsed between loading and unloading due to delivery distance. This can be expressed as follows:

\[ \frac{n_p v_c}{s_c} \geq R_f \] (10.17)

In this case, \( R_f \) must be interpreted as a system specification required of the recirculating conveyor.

3. **Uniformity Principle.** This principle states that parts (loads) should be uniformly distributed throughout the length of the conveyor, so that there will be no sections
of the conveyor in which every carrier is full while other sections are virtually empty. The reason for the uniformity principle is to avoid unusually long waiting times at the load or unload stations for empty or full carriers (respectively) to arrive.

**EXAMPLE 10.4  Recirculating Conveyor Analysis: Kwo**

A recirculating conveyor has a total length of 300 m. Its speed is 60 m/min, and the spacing of part carriers along its length is 12 m. Each carrier can hold two parts. The task time required to load two parts into each carrier is 0.20 min and the unload time is the same. The required loading and unloading rates are both defined by the specified flow rate, which is 4 parts/min. Evaluate the conveyor system design with respect to Kwo’s three principles.

**Solution:**  *Speed Rule:* The lower limit on speed is set by the required loading and unloading rates, which is 4 parts/min. Checking this against Eq. (10.15),

\[
\frac{n_p v_c}{s_c} \geq \text{Max}\{R_L, R_U\}
\]

\[
\frac{(2 \text{ parts/carrier})(60 \text{ m/min})}{12 \text{ m/carrier}} = 10 \text{ parts/min} > 4 \text{ parts/min}
\]

Checking the lower limit,

\[
\frac{60 \text{ m/min}}{12 \text{ m/carrier}} = 5 \text{ carriers/min} \leq \text{Min}\left\{\frac{1}{0.2}, \frac{1}{0.2}\right\} = \text{Min}\{5, 5\} = 5
\]

The Speed Rule is satisfied.

*Capacity Constraint:* The conveyor flow rate capacity = 10 parts/min as computed above. Since this is substantially greater than the required delivery rate of 4 parts/min, the capacity constraint is satisfied. Kwo provides guidelines for determining the flow rate requirement that should be compared to the conveyor capacity.

*Uniformity Principle:* The conveyor is assumed to be uniformly loaded throughout its length, since the loading and unloading rates are equal and the flow rate capacity is substantially greater than the load/unload rate. Conditions for checking the uniformity principle are available; the reader is referred to the original papers by Kwo [8], [9].

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**REFERENCES**


