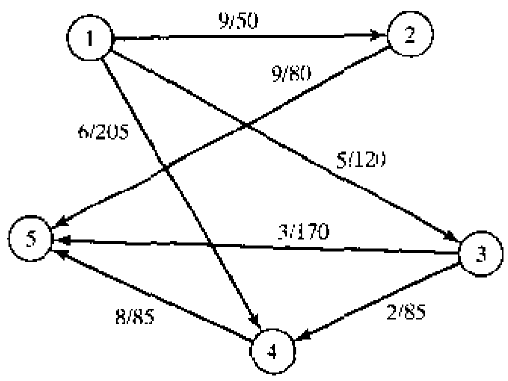

Figure 10.14 Flow diagram showing material deliveries between load/unload stations. Arrows indicate flow rates and distances (same data as in Table 10.2), and nodes represent load/unload stations.

Muther and Haganas [19] suggest several graphical techniques for visualizing transports, including mathematical plots and flow diagrams of different types. The flow diagram in Figure 10.14 indicates movement of materials and corresponding origination and destination points of the moves. In this diagram, origination and destination points are represented by nodes, and material flows are depicted by arrows between the points. The nodes might represent production departments between which parts are moved or load and unload stations in a facility. Our flow diagram portrays the same information as in the From-To Chart of Table 10.2.

10.6.2 Analysis of Vehicle-Based Systems

Mathematical equations can be developed to describe the operation of vehicle-based material transport systems. Equipment used in such systems include industrial trucks (both hand trucks and powered trucks), automated guided vehicles, monorails and other rail guided vehicles, certain types of conveyor systems (e.g., in-floor towline conveyors), and certain crane operations. 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 or other reasons. 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

$$T_c = T_L + \frac{L_d}{v_c} + T_U + \frac{L_e}{v_c} \tag{10.1}$$

where T_c = delivery cycle time (min/del), T_L = time to load at load station (min), L_d = distance the vehicle travels between load and unload station (m, ft), v_c = carrier velocity (m/min, ft/min), T_U = time to unload at unload station (min), and L_e = distance the vehicle travels empty until the start of the next delivery cycle (m, ft).

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 preceding 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 2.4.3) 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* T_f 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 there is no blocking of vehicles, then $F_t = 1.0$. As blocking increases, the value of F_t decreases. Blocking, waiting at intersections, and vehicles 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, little or no blocking should occur, and the traffic factor will be very close to 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 the low operating performance sometimes observed in these systems. Their performance is very dependent on the work efficiency of the operators who drive the trucks. Let us define *efficiency* here as the actual work rate of the human operator relative to work rate expected under standard or normal performance. Let E 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, T_f, and E. That is,

$$AT = 60\,A\,T_f E \tag{10.2}$$

where AT = available time (min/hr per vehicle), A = availability, T_f = traffic factor, and E = worker efficiency. The parameters A, T_f, and E do not take into account poor vehicle routing, poor guidepath 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:

$$R_{dv} = \frac{AT}{T_c} \tag{10.3}$$

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 follows:

$$WL = R_f T_c \tag{10.4}$$

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

$$n_c = \frac{WL}{AT} \tag{10.5}$$

where n_c = number of carriers required, WL = workload (min/hr), and AT = available time per vehicle (min/hr per vehicle). It can be shown that Eq. (10.5) reduces to the following:

$$n_c = \frac{R_f}{R_{dv}} \tag{10.6}$$

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

Given the AGVS layout shown in Figure 10.15. 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. It is desired to determine 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 = 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.

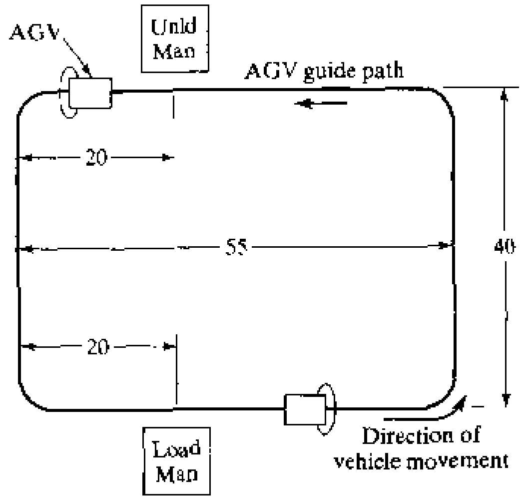

Figure 10.15 AGVS loop layout for Example 10.1. Key: Unld = unload, Man = manual operation, dimensions in meters (m).

Solution: (a) Ignoring effects of slightly shorter distances around the curves at corners of the loop, the values of L_d 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.

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

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

Therefore, the number of vehicles required is

$$n_c = \frac{202}{51.3} = 3.94 \text{ vehicles}$$

This value should be rounded up to $n_c = 4$ 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 10.15, determining these values is straightforward. For a complex AGVS layout, the problem is more difficult. The following example illustrates this issue.

EXAMPLE 10.2 Determining L_d for a More-Complex AGVS Layout

The layout for this example is shown in Figure 10.16, and the From-To Chart is presented in Table 10.2. The AGVS includes load station 1 where raw parts