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OPTIMIZATION STUDY OF AGV SYSTEM DESIGN

BY

Susan Ann Dick

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in
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Certificate of Approval

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ABSTRACT

As the most flexible, unmanned material handling system, automated guided vehicles (AGV) are being used in many flexible manufacturing systems. However, designing an optimized AGV system can involve months of planning. Knowledge of which design variables have the largest impact on an AGV system would reduce the design time.

This research project examines a set of AGV design variables to determine which have the largest impact on an AGV system. The impacts of these variables (track layout, delivery load, number of extra vehicles, load/unload time, segment control size, and delivery distance), are evaluated with respect to four optimization goals: maximize the traffic factor, minimize the number of vehicles, minimize system response, and flexibility to adapt to changing production needs.

The number of extra vehicles has the largest impact on the AGV system design. One extra vehicle, beyond the vehicles required to minimally service the material delivery requests, needs to be added to the factory to balance the traffic factor and system response time.

The design of the track is critical to optimizing the AGV system. However, it is clear that a detailed simulation would be required to design the optimal track. Developing general track guidelines for this facility is not possible.

Finally, the ability of the AGV system to withstand future manufacturing process changes was evaluated by changing the delivery distance and the delivery load (deliveries per hour). All four layouts were able to

accommodate manufacturing process changes without major material handling system changes.

INTRODUCTION

With increased global competition, manufacturers are turning to computer integrated manufacturing and flexible manufacturing systems to remain competitive. Among the key components in a flexible manufacturing system is the material handling system which links the pieces of manufacturing equipment or workstations.

The Automated Guided Vehicle System (AGVS) is the most flexible unmanned material handling system available in industry today. As a result, AGVs are often the material handling system of choice for flexible manufacturing system design.

Description of the Problem

The flexibility available in an AGV system inherently makes designing and procuring such a system complex. Table 1 shows a listing of the AGV variables which can be evaluated during the AGV system design. The combinations of system design variables are staggering and a detailed simulation of the manufacturing facility is the only way to design an optimal AGV system.

With the large number of design variables, simulation can be a very complex process taking months to evaluate all the options. If one knew ahead of time which variables had the largest effect on the AGV system, the process of simulating the AGVS would be much less time consuming, and much less complex because simulation could focus on key variables.

AGV Design Variables
Number of vehicles
Vehicle speed
Vehicle acceleration/deceleration
Vehicle charging
Vehicle collision control
Number of loads per vehicle
Vehicle guidance
Vehicle dispatching rules
Task assignment rules
Empty vehicle policy
Track design
Uni- vs bi-directional track
Park spurs
Load/unload spurs
Track control segment size
Material delivery distances
Delivery routes
Intersection design
Load scheduling
Deliveries per hour
Load/unload times

Table 1. List of AGV Design Variables

Objective of Research

The objective of this research project is to take a subset of all the possible AGV design variables and determine what effect they have on the design of an AGV system. However, the effect of the design variables can only be measured if there are parameters to optimize. For this project, there will be four goals upon which to design an optimized AGV system.

One important goal is to maximize the amount of material transported by each vehicle. To maximize the material transported, the amount of time a vehicle is blocked waiting for a vehicle to move out of its way must be minimized. The measure of the time a vehicle spends moving product (not blocked) is called traffic factor and is defined by Fitzgerald [14] as "a measure of a vehicle's 'competition' for a guidepath". The traffic factor can vary from zero to one, where a value of one means a vehicle spends all its time productively moving product. According to Fitzgerald, in properly designed AGV systems, traffic factor varies between 0.85 and 1.0. "If the traffic factor is less than 0.85, the AGV network is poorly designed." Fitzgerald [14] This indicates that the variables used to design the AGV network influence the traffic factor. Table 1 lists AGV design variables and therefore is a list of the variables which influence traffic factor. The first design goal is to maximize the traffic factor.

The AGV vehicle cost is a significant portion of the AGV system cost. Therefore, an additional goal is to minimize the number of vehicles required. In contrast with this goal is the need to provide the fastest response time to requests for material transportation.

The final goal is to design a system which can adapt to the changes in the current products made in the factory and the introduction of new products. This goal can be tested by changing the average distance required to make material deliveries. When a factory is first built, the workstations are often located to minimize material transport distances. However, as the products change, the order of the manufacturing processes changes, resulting in an increase in material transport distances. The adaptability of the material handling system design is also tested by increasing the number of material deliveries required in the facility. This evaluates how expanded production will affect the material handling system.

In summary, the four design goals are:

1. Maximize the traffic factor
2. Minimize the number of vehicles
3. Minimize system response time
4. A design which is flexible for changing production needs.

As indicated earlier, there are a large number of possible AGV design parameters. For this research project, a subset of variables in Table 1 will be used to design an AGV system and evaluate the effect on the four goals. The design variables chosen for this evaluation are:

1. Number of branching segments or short-cuts designed into the track
2. Number of deliveries per hour
3. Number of extra AGVs
4. Material load/unload time
5. Use of spurs for loading/unloading
6. Size of track control segments
7. Delivery distance

LITERATURE SEARCH

Overview of AGV Implementation

The first large scale use of AGVs in manufacturing was in 1974 in the Volvo plant in Kalmar, Sweden. Since then, AGVs have been appearing more frequently in manufacturing installations as a means of achieving high manufacturing flexibility. Many authors report on the successful implementation of AGV systems, among them Gould [21] and Muller [37]. In his article, Gould details the successful implementation of AGVs at GM's Oshawa truck assembly plant. Through installing 424 AGVs, the GM plant was able to realize "an unprecedented degree of manufacturing flexibility" and more ergonomic work stations. Muller details the success Europeans have had in installing AGVs. Included in his book is a detailed list of the major European installations.

To aid people who are new to the AGV industry, many people have written articles on the basics of AGV systems. A sampling of these articles include Adams [1], Bose [3], Gould [20], Higgins [25], Jacobson [26], Koff [30], Koff [31], Miller [35], and Zygmont [51]. These articles provide two general types of information. The first are recommendations on what types of installations could benefit most from an AGV material handling system. Secondly, these articles provide information on AGV hardware and control issues such as vehicle types, guidance systems and traffic control.

AGV Dispatching Policies

Determining which vehicle to dispatch to a request can have a large impact on the number of vehicles required to do the job, and the time to service each request. Egbelu and Tanchoco [12] and Cheng [6] have explored AGV distance and AGV attribute-based rules for assigning vehicles to requests.

A second way to approach this issue is to assign vehicles to jobs based on a job priority system. Egbelu [8] and Han and McGinnis [24] suggest dispatching vehicles based on the state of the workstation for which the load is destined. This system serves to deliver parts just in time, while trying to minimize station idle time.

Moreno et al. [36] propose a plan-based dispatching system. In this system, jobs are assigned to vehicles as they come in, before the vehicles become idle. This system anticipates where vehicles will be in the future to minimize the time required for jobs to be serviced.

Egbelu and Roy [10] explore how best to dispatch material into the production facility to minimize the wait time and the idle time. They examine a system where the material remains on an AGV through the entire manufacturing process. This concept is unique; product flow and vehicle flow through the factory cannot be separated.

AGV System Design

A wide variety of options in designing AGV systems have been offered by researchers. Ashayeri [2] presents a mathematical model for flow path design when the layout of the factory is known. Gaskins and Tanchoco [16] present a mathematical approach for designing a flow path which minimizes the total travel of loaded vehicles. The output of their model is an optimized factory layout. Goetz and Egbelu [18] build on the work of Gaskin and Tanchoco by proposing a heuristic approach to the problem which allows for the design of larger factories.

Tanchoco and Sinriech [49] suggest using a single-loop guide path. In this design, the vehicles travel around a ring, eliminating the need for intersections. The trade-off with this system is gaining simplicity in system control while requiring additional vehicles. They propose using a bi-directional track as a way to reduce the number of vehicles required. A similar system presented by Bozer and Srinivansan [4] uses multiple single-loop guide paths, with one vehicle servicing each loop. There are queues between the guide paths to allow product to pass from one vehicle to the next. As with the single-loop guide path, this system eliminates the need for intersections and further eliminates congestion due to blocking. However, this system requires more floor space and is less tolerant of vehicle breakdowns.

Most conventional AGV systems allow vehicles to travel only in one direction. Egbelu and Tanchoco [11] propose a system which allows vehicles to travel in two directions. They explore systems with parallel tracks where vehicles can travel in two directions but not on the same track, and systems where some track segments are bi-directional. This system does provide efficiencies over the conventional uni-directional systems especially where there are limited numbers of vehicles. Ozden [39] explored a system which combines the approaches of Tanchoco and Sinriech [49] and Egbelu and Tanchoco [11]. Ozden combines using bi-directional track, multi-capacity AGVs and queues at the work stations to produce a system capable of larger throughput than is available with only one of these options.

Number of Vehicles

Determining the number of vehicles required to service a factory is one of the first steps in determining the overall cost of implementing an AGV system. Several methods to calculate the number of vehicles are mathematically based, Fitzgerald [14], Egbelu [9], and Tanchoco et al. [48]. Schmidt [44] and Kasilingam [27] have developed models which minimize overall system cost as a way to determine the number of vehicles required. Newton [38] has written a short Fortran simulation program to solve this problem, but the simulation cannot take into account many of the details typically required of simulation models. As a result, this model is only good for a first pass determination of the number of vehicles required.

Simulation

Simulation is the best way to get a detailed analysis of an AGV system. Using simulation to design material handling systems is described in several general articles: Kerpchin [28], [29], Maxwell [33], and Phillips [40]. There are many simulation languages available for analyzing AGV systems. Chang et al. [5] describe the use of SLAM^R [1] and Gaskins and Tanchoco [15] the use of AGVSim2. Unfortunately, many of the simulation languages are complex. Gong and McGinnis [19] have written a simulation code generator to simplify the simulation process.

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[1] SLAM^R is a registered trademark of Pritsker & Associates, Inc.

Simulation can be used to solve several types of manufacturing design issues. Ulgen and Kedia [50] show how simulation is used to design an AGV-based assembly plant. Lee et al [32] used simulation to evaluate the effects of several design parameters (i.e. number of vehicles, vehicle speed) on the AGV system performance.

DESCRIPTION OF THE SIMULATION EXPERIMENTS

As stated previously, the objectives of this research were to evaluate a subset of AGV design variables to satisfy the four goals. The tool used to do the evaluation was computer simulation using SLAM^R, a simulation package by Pritsker & Associates, Inc. [41].

Parameter Selection

SLAM^R is a very flexible simulation package which allows the system modeler many options in specifying how the AGV layout will look and what rules govern its operation. To describe to SLAM^R the characteristics of an AGV system, the vehicle characteristics, handling of material requests, track layout, and material-movement scheduling must be specified. What follows is a description of the available SLAM^R AGV variables and how they were fixed for this evaluation.

Vehicle Characteristics

SLAM^R allows the user to define what type of AGV is used: how long it is, how fast it goes, acceleration rates, and how many loads it can carry at one time. For this evaluation, the vehicle is 5 feet long, travels at a constant 3 ft/sec, and can carry one unit load.

SLAM^R requires information on how to handle empty vehicles which do not have a request to service. To minimize traffic congestion, these vehicles will pull off the main AGV track onto one of two parking spurs. These parking spurs were intentionally designed on opposite sides of the factory to minimize the distance the vehicles had to travel to the parking spurs, and ultimately to their next assignment. Other empty vehicle options in SLAM^R include having the vehicle stop on the track until it receives a move request, or having the vehicle roam the track. Both of these options would severely increase the traffic congestion.

Finally, one must define which vehicle services a request when more than one vehicle is available. The two options available in SLAM^R are FIFO in which the vehicle which has been idle longest services the call, and CLOSEST where the vehicle which is closest to the request is chosen. The CLOSEST option was chosen because it minimizes the time to service a delivery request.

Material Requests

Requests to move a load of material are queued in a buffer while waiting assignment to an AGV. A request is assigned to a vehicle only when a vehicle becomes idle. Assigning the material delivery request to a vehicle can be done in several ways:

1. First in, first out (FIFO) basis - the oldest job request serviced first.
2. Last in, first out (LIFO) - the newest job gets serviced first.
3. The job which is closest to the idle vehicle gets serviced.

FIFO guarantees that all jobs get handled in a timely manner. In contrast, LIFO could cause a few jobs to wait a long time for service, and assigning jobs closest to the idle vehicle could also cause a few jobs to wait a long time especially if a manufacturing workstation is located far from the other workstations. Since minimizing the time to service material-movement requests was a goal of this project, FIFO was chosen to determine which jobs get assigned to idle vehicles.

Track Design

Using $SLAM^R$, there are nearly infinite possible AGV track layouts. For this project, four manufacturing layouts were designed and evaluated. In all cases, there are nine pick-up/drop-off locations (workstations), and two parking spurs. In layout A (see Figure 1), the departments are laid out in a 3 by 3 grid. All adjacent departments in the layout are connected. In layout B (see Figure 2), the departments are laid out in a 3 by 3 grid, but several adjacent departments are no longer connected. Therefore, the average distance the AGVs have to travel is greater. In the third layout (see figure 3), all nine departments are located on a loop. This layout maximizes the distance the vehicles have to travel between departments. The final layout, layout D, (see figure 4) is similar to Layout C except all the departments are on spurs. The vehicle leaves the main track to deliver a load, and then returns to the main track.

$SLAM^R$ allows for vehicles to travel either in one direction only, or in both a forward and backward direction across the same section of track (bi-directional). Unfortunately, if the track is not designed correctly, a bi-directional system can grid-lock and manual intervention is required to free the vehicles. As a result, in the four simple layouts used here, only uni-directional travel is allowed.

Track segment control is used to avoid vehicle collisions. In this scheme, the track layout is divided into segments, where only one vehicle can be in a segment at a time. A vehicle seizes control of the segment as it enters the segment, and does not relinquish control until

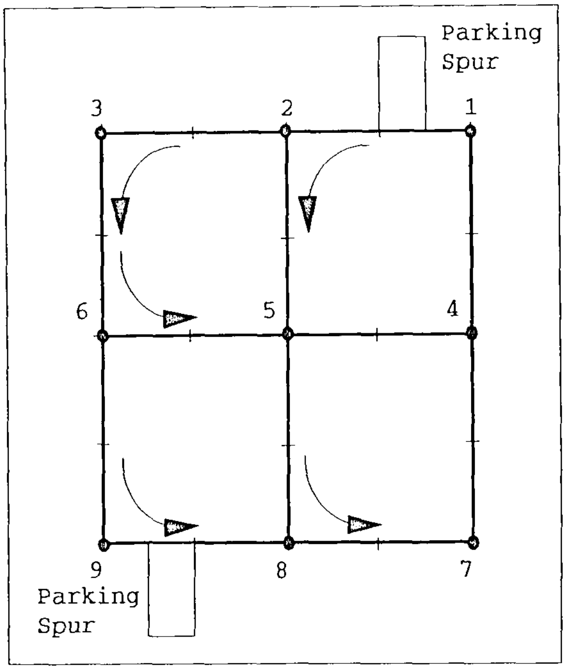

Figure 1. Track A with 40 foot control segments.

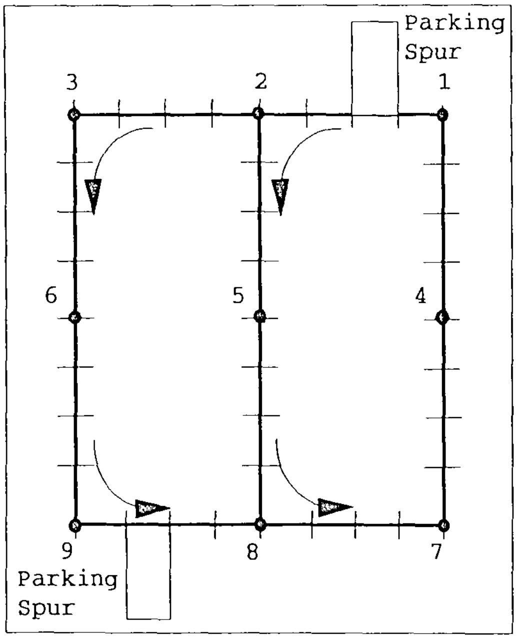

Figure 2.Track B with 20 foot control segments.

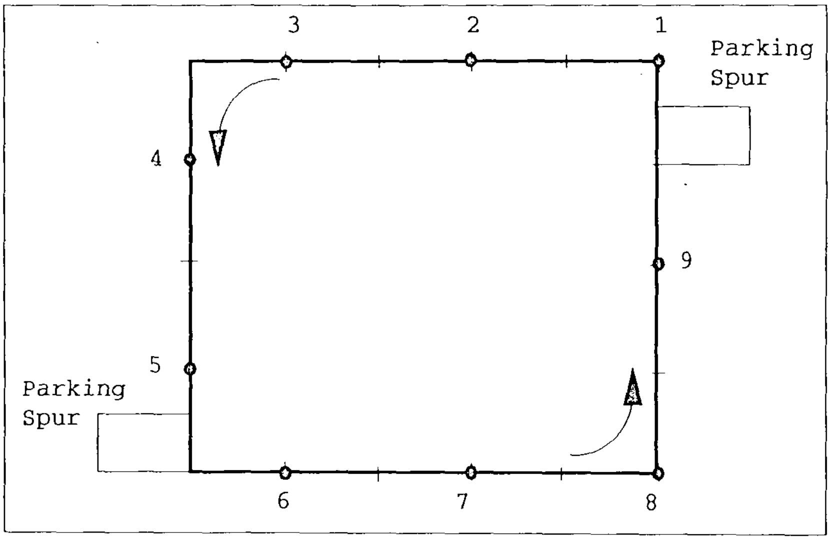

Figure 3. Track C with 40 foot control segments

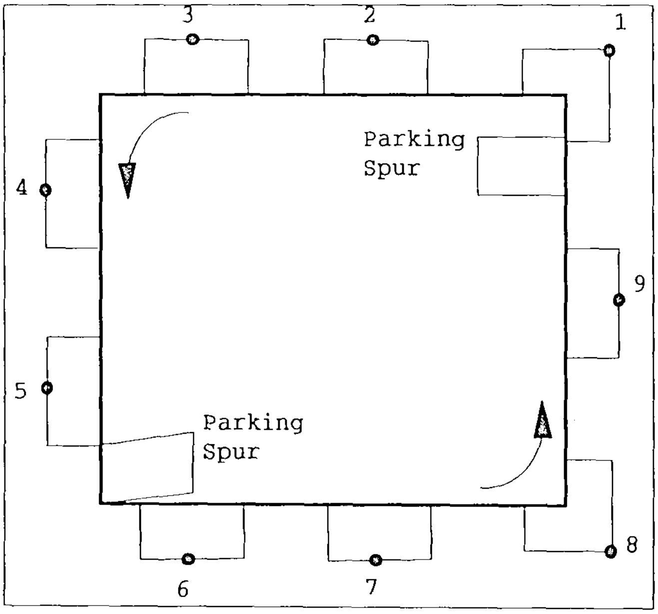

Figure 4. Track D with Load/unload Spurs

it exits the segment. Since the size of the segment can contribute to excessive traffic congestion, several different segment lengths, 10, 20 and 40 feet, are being evaluated.

Material Movement

The factory modeled here makes two kinds products. Each product requires four manufacturing operations. The product begins in the warehouse (workstation 1), progresses to four workstations, and finally back to the warehouse. Therefore, during the manufacturing process, each product is moved by the materials handling system five times.

Since this is a newly designed factory, the delivery of product progresses logically from one workstation to the next adjacent workstation and finally back to the warehouse. However, as the products built in this factory change, a logical flow from one workstation to the next may not be possible. As a result, two types of delivery systems are being evaluated, see Figure 5. In the first delivery system, movement is between adjacent departments, and in the second, deliveries are frequently made from one side of the factory to the other. This will indicate how traffic congestion in the factory may change over the life of the factory.

Two additional delivery parameters were evaluated in the simulation. In all the layouts except D, the vehicles load and unload product from the main AGV track. Excessive load/unload time can result in significant vehicle blocking. To determine the contribution of load/unload time, the times were varied from 5 to 25 seconds. Another parameter which was varied was the number of delivery requests made per hour. As the number of requests increased, more vehicles would be placed in a given area, possibly causing congestion. For this evaluation, the number of requests per hour ranged from 60 to 180.

Description of SLAM^R Model

The model begins by creating entities at predetermined intervals. Figure 6 shows a network drawing of the SLAM^R model. As an example, when there are 60 deliveries per hour, the model creates a new entity every minute. This entity is then assigned a material delivery request. As indicated earlier, for the two products made in the factory, there are ten unique material moves from one workstation to another (five moves for each product made). Each material move has an equal probability (.1) of occurring. When SLAM^R creates a new entity (material move request), it randomly assigns the request so that each material move occurs ten percent of the time on the average.

Once created, the material move request is placed at the bottom of the queue and awaits its turn to be serviced. When it is at the top of the list, the next available AGV services the request by picking up the designated load and unloading it at its final destination. When the move request is completed, the AGV is assigned to another move request, or it parks in the parking spur waiting for a delivery request.

Procedure for Running the Simulation

Each simulation was run for 50000 seconds (approx 14 hours), however much of this time was spent reaching steady state. (Steady state for

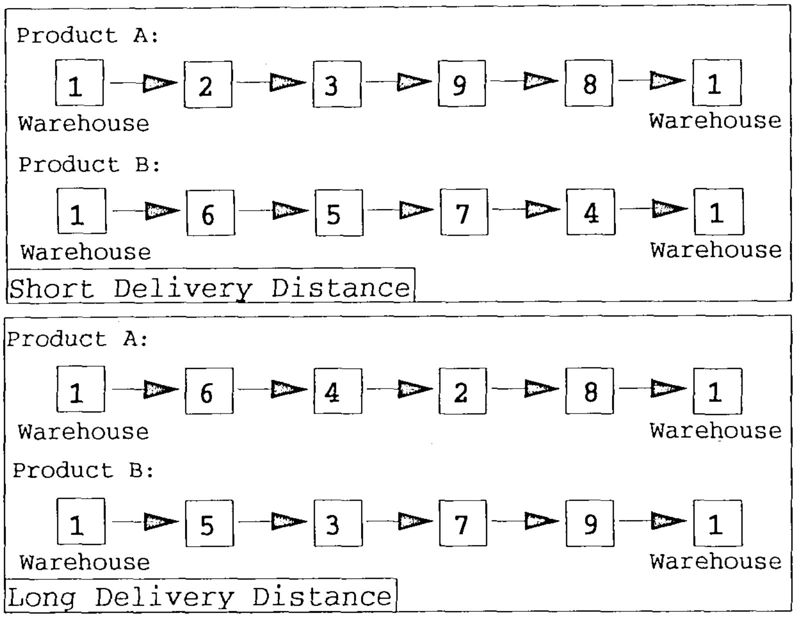

Figure 5. Product Routings

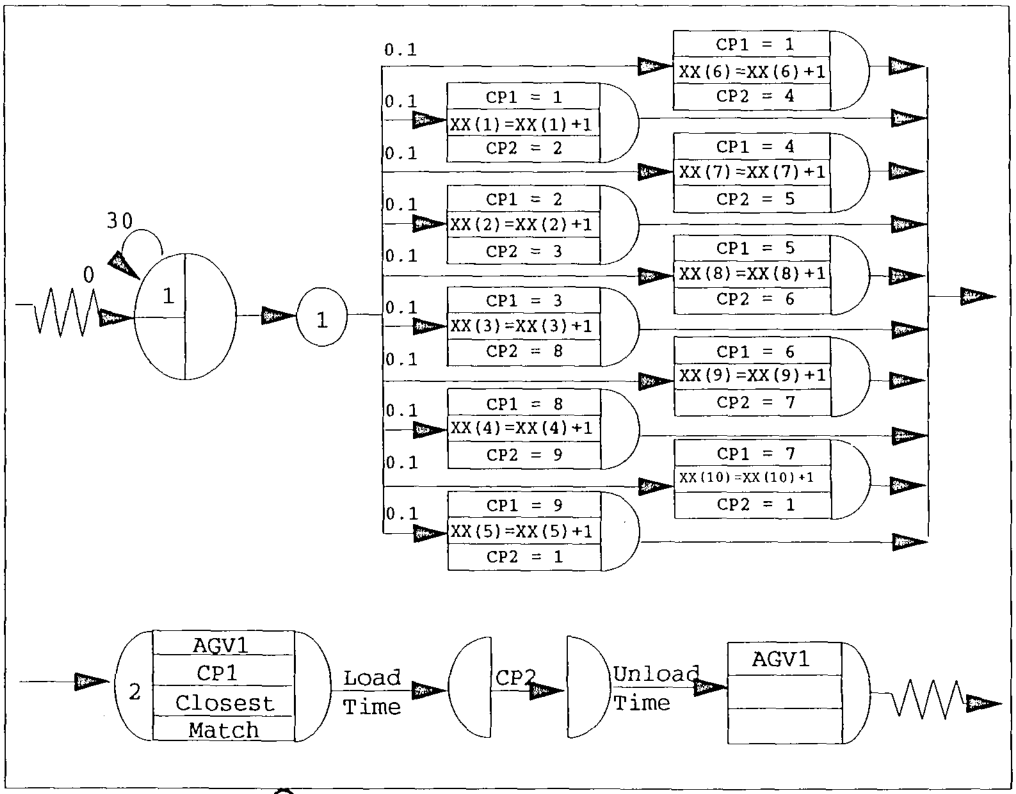

Figure 6. SLAM® Simulation Network

all the simulations was reached by 40000 seconds.) Since factories typically run at steady state except after the plant start-up, the data used for analysis were collected between time 40000 and 50000 seconds (2.8 hours). To minimize experimental error, each simulation was run twice. A different random number seed was used for the two runs to change the order of the delivery requests. Data from both simulations were used in the data analysis. Appendix A shows a list of the simulations which were run.

For each combination of AGV parameters, several simulations were run to determine the minimum number of vehicles required to service the factory's material-movement requests. Once the minimum number of vehicles required was determined, the simulation was repeated an additional 5 times, adding one vehicle each time to test the effect of extra vehicles on AGV system performance. In total, 672 simulations were run.

Simulation Data

The simulation data provide a detailed accounting of the vehicle activities, and information on the system response time. The vehicle activities were categorized into the following groups:

- Traveling to load - empty
- Loading
- Traveling to unload - full
- Unloading
- Traveling empty blocked
- Traveling full blocked
- Traveling idle
- Stopped idle

For analysis purposes, these are regrouped into the following 5 categories:

1. Traveling empty to a job
2. Traveling full
3. Loading/unloading
4. Idle - either traveling or stopped
5. Blocked - either full or empty

SLAM^R reported system response time in two different ways. First, system response time is reported as the average time required to assign a job to a vehicle, and second, the time required to assign the job and have the vehicle arrive at the load station. The ultimate judge of system response time is the time required for a vehicle to arrive at the load station. Therefore, for this analysis, the system response time is defined as the time required to assign the job and have the vehicle arrive to pick up the materials.

Traffic Factor

The traffic factor is the percent of the time a vehicle spends productively moving product. Three vehicle states are considered productive activities, traveling empty to a job, traveling full, and loading/unloading. Blocked time is considered unproductive time, and idle time is considered neutral time (neither productive nor unproductive).

The formula for the traffic factor is:

$$Tf = 1 - \frac{\text{Non-Productive time}}{(\text{Productive time} + \text{Non-Productive time})} \qquad [1]$$

Using the simulation data, the traffic factor would be:

$$Tf = 1 - \frac{\text{Blocked}}{(\text{Blocked} + \text{Empty} + \text{Full} + \text{Load} + \text{Unload})} \qquad [2]$$

However, this can be simplified to:

$$Tf = 1 - \frac{\text{Blocked}}{(1 - \text{Idle})} \qquad [3]$$

The data used in these equations are expressed as a percent of the time a vehicle is in each state. This results in the following equation:

$$1 = \text{Blocked} + \text{Empty} + \text{Full} + \text{Load} + \text{Unload} + \text{Idle} \qquad [4]$$

MODEL DEVELOPMENT

SAS^R Models

The statistical package SAS^R [2] was used to develop mathematical models from the simulation data. Two models were generated, one for the traffic factor and one for the time to respond to delivery request, to assist in determining which design parameters affected the four optimization goals. However, analyzing the traffic factor using only the traffic factor model is difficult because there are many competing factors which contribute to the traffic factor. Equation 3, page 22, shows the most simplified version of the traffic factor calculation. Using this equation, an analysis of idle and blocked models will give a better overall understanding of the traffic factor model. As a result, SAS^R models were generated for both blocked and idle time.

Each model is composed of a combination of seven variables. Three of the variables are qualitative or class variables: track type, load/unload spurs, and delivery distance. The other four variables, load/unload time, segment size, deliveries per hour, and number of vehicles, are continuous variables.

When developing the model, the degrees of freedom for each variable are used to determine how the variable can be used in the model. As an example, segment size is evaluated in the simulations at three levels (i.e. 10 ft, 20 ft, and 40 ft) and therefore has two degrees of freedom

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[2] SAS^R is a registered trademark of SAS Institute Inc., Cary NC, USA.

(Degrees of Freedom = number of levels minus one). Therefore, segment size can appear in the model as a second order polynomial with linear and quadratic terms. Both load/unload time and deliveries per hour were also evaluated at three different levels and can be used in the model as linear or quadratic terms. The number of extra vehicles was evaluated at five different levels so it could appear as a linear, quadratic, third order or fourth order polynomial. The qualitative variables have only one degree of freedom so they can only appear in the model as linear terms.

Data Transformations

The variables used in the models varied over different ranges (i.e. the number of deliveries per hour varies from 60 to 180 while the number of vehicles varies from 0 to 5). Since deliveries per hour varies over a much larger range, it can appear mathematically to contribute more significantly to traffic factor than the number of extra vehicles. This statistical analysis problem is called multicollinearity and is resolved by transforming all the variables to the same range (-1 to +1) before being used to generate the models. As an example, the variable deliveries per hour is transformed so 60 deliveries per hour became -1, 120 became 0, and 180 became +1. Appendix B shows a listing of the transformation equations used.

The variable vehicle received additional transformations before it was used in the models. The simulation output gave the number of vehicles used in the simulation. However, the important parameter is the number of extra vehicles used in the simulation above what was required to reach steady state. The number of extra vehicles was the variable used in the models.

Model Formulation

The SAS^R procedures used in developing the models were PROC STEPWISE [43] and PROC GLM [42]. PROC STEPWISE was used to determine which independent variables were statistically significant enough to include in the model. In this analysis, a 95% confidence was used to include a variable in the model. Once the variables for inclusion in the model were determined, PROC GLM was used to determine the mathematical model.

R-Square was used as a measure of how successfully the model explained the experimental data. A target of 0.7 (70% of the experimental data are explained by the model) was chosen, but in most cases, the R-Square value was greater. In addition, plots of residuals were made for all models to ensure that there was not an obvious bias.

A major goal of this project was to build mathematical models to determine the influence of each design variable on the four optimization goals. However, since the models include many linear combinations of variables, it is difficult to determine the influence of each variable from the mathematical model. To determine the effect of each variable, a technique called correlated histograms is used. This technique averages all the response variables at each level of the variable. As an example, for segment size, an average traffic factor is calculated for all simulation runs made at a segment size of 10 ft, another average for 20 ft and another for 40 ft, as shown in figure 7. This technique indicates the effect of each design variable independent of the other design variables.

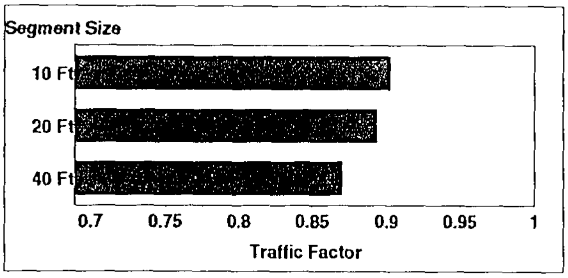

Figure 7. Example of Correlated Histograms

RESULTS

Maximizing Traffic Factor

As indicated in the previous section, the traffic factor is calculated using the vehicle blocked time and the vehicle idle time, as shown in equation 3 on page 22. To understand which AGV design parameters maximize the traffic factor and why, it is important to examine the influence of the AGV design parameters on blocked and idle time.

Blocked Model

Using SAS^R, a general model was developed to show the relative contributions of the AGV design parameters to the time a vehicle is blocked. Figure 8 shows the mathematical model. The R-Square for the model was 0.92, meaning 92 percent of the variation in the simulation data is explained by the model. To determine the influence of each AGV parameter, correlated histograms are used. Figure 9 shows the correlated histograms for the blocked model. Table 2 details the relative contribution of the AGV design parameters to the blocked model.

The number of extra vehicles had the largest influence on the time a vehicle is blocked. In general, as each successive vehicle was added, the blocked time went up significantly. Adding the first two extra vehicles added only 0.8 percent to the blocked time, but the fourth and fifth vehicles added almost 5 percent each. The relationship between extra vehicles and percent time blocked is exponential. The reason for the strong relationship between number of extra vehicles and blocked

$$
\begin{aligned}
\text{Block} = {} & -0.158 + 0.322*\text{Veh}_T^4 + 0.500*\text{Veh}_T*\text{Del}_T + 0.171*\text{Veh}_T*\text{Lu}_T \\
& + 0.211*\text{Veh}_T*\text{TrackC} + 0.515*\text{Veh}_T*\text{Long} + 0.416*\text{Veh}_T*\text{Short} \\
& + 0.108*\text{Veh}_T*\text{Seg}_T - 0.255*\text{Del}_T*\text{Long} - 0.463*\text{Del}_T*\text{Short} \\
& - 0.529*\text{Veh}_T^3 + 0.093*\text{Veh}_T*\text{TrackA} - 0.062*\text{Lu}_T*\text{Long} \\
& - 0.210*\text{Lu}_T*\text{Short} + 0.247*\text{Lu}_T*\text{TrackA} + 0.265*\text{Lu}_T*\text{TrackB} \\
& + 0.311*\text{Lu}_T*\text{TrackC} + 0.167*\text{Del}_T*\text{TrackA} + 0.093*\text{Del}_T*\text{TrackB} \\
& + 0.218*\text{Del}_T*\text{TrackC} + 0.148*\text{Del}_T^2 + 0.147*\text{Lu}_T^2 + 0.082*\text{Seg}_T^2 \\
& - 0.082*\text{Seg}_T*\text{TrackB}.
\end{aligned}
$$

Seg_T = Segment Size (Transformed)
Del_T = Deliveries Per Hour (Transformed)
Lu_T = Load/Unload Time (Transformed)
Veh_T = Number of Extra Vehicles (Transformed)
Short= Short Delivery Distance
Long = Long Delivery Distance

NOTE: All continuous variables were transformed before running the model. See Appendix 2 for the transformation equations.

Figure 8. Blocked Mathematical Model

Design Variable	Percent Effect
Deliveries Per Hour	5.0
Segment Size	2.6
Extra Vehicles	12.6
Load/Unload Time	5.3
Track Layout	
Remove one branch	-1.4
Remove 2nd branch	1.8
Spurs	-2.5
Delivery Distance	-0.4

Table 2. Effect of design parameters on Blocked model.

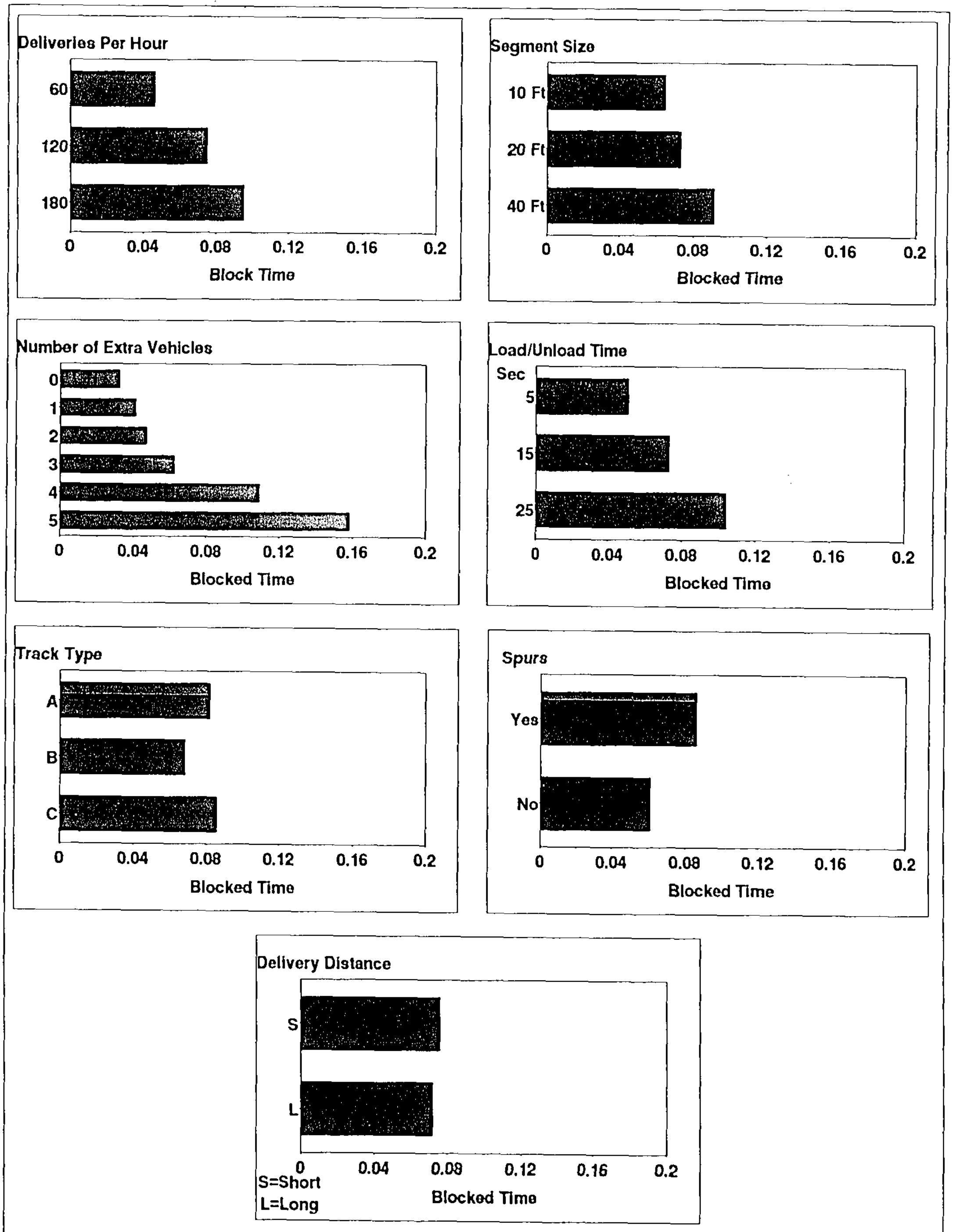

Figure 9. Blocked Correlated Histograms

time is straightforward. The more vehicles on the AGV track, the more congestion there is on the track.

The number of deliveries per hour and load/unload time had nearly equivalent effects on the blocked model. Over the range examined, both variables accounted for approximately a 5 percent increase in the time a vehicle was blocked. Adding more deliveries to the factory increases the AGV traffic, and the increased congestion causes more vehicle blocking. The load/unload time also contributed to extra blocking because vehicles loaded and unloaded material while they were on the main track.

Increasing the size of the track control-segments can cause up to a 2.6 percent increase in vehicle blocking. With long track control-segments, a vehicle takes longer to get through the segment causing a greater occurrence of vehicles blocked waiting for access to the segment.

Adding load/unload spurs to the track decreased the vehicle blocking by 2.5 percent. The decrease in blocked time resulted from a vehicle not holding up other vehicles while loading or unloading.

The effect of removing branching segments in the layout had mixed results. On going from track A to track B, the blocked time was decreased by 1.4 percent. Removing one branch in the layout resulted in removing two places where the vehicles merged together (See figure 10) resulting in less vehicle blocking. At the same time, removing one branch increased the distance the vehicles had to travel to deliver

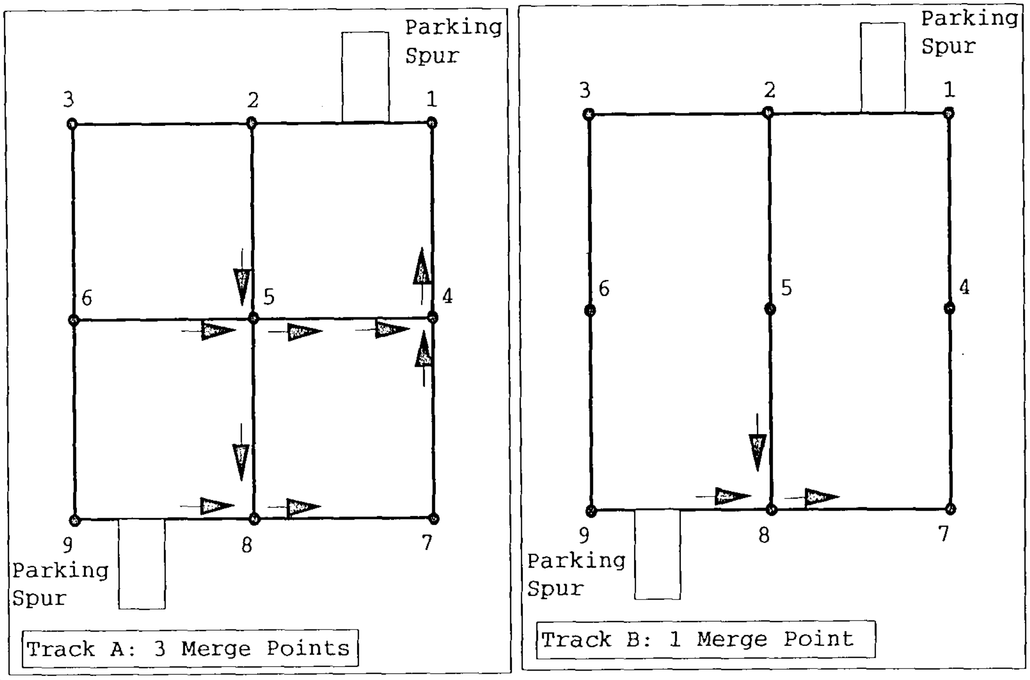

Figure 10. Comparison of Merging Points

loads, causing an increase in vehicle blocking. In this case, removing two merging intersections had a larger effect resulting in an overall decrease in blocked time. However, removing one additional branch, going from track B to track C, resulted in an increase in vehicle blocking of 1.8%. Although the one remaining merge intersection in the layout was removed, this could not compensate for the drastic increase in the distance vehicles traveled to deliver loads.

The final design factor, going from a delivery system where the deliveries are made to neighboring stations, to a system where the deliveries are spread throughout the factory, had very little impact on blocking. Going from short to long delivery distances decreased the blocking 0.4 percent.

Idle Model

Using SAS^R Procedure GLM [42], a model was built to characterize the influence of the AGV design parameters on vehicle idle time. Figure 11 shows a full description of the model. The R-square for the model was 0.93. To analyze the model, correlated histograms were plotted and used to determine the influence of each AGV parameter. Figure 12 shows the correlated histograms, and Table 3 shows a numerical tabulation of the data.

As with the blocked model, the number of extra vehicles had the largest influence on idle time. However, in this model, the first two extra vehicles had the largest influence. Adding the first vehicle increased idle time by 6.5 percent, and the second vehicle added 16.7 percent. The last two vehicles only added 2 percent and 0.8 percent respectively. The dramatic decrease in additional idle time results from the extreme congestion on the tracks because of the extra vehicles. Percent blocked time and percent idle time counterbalance each other; the more blocked time, the less idle time.

Decreasing the system delivery demands resulted in an increase in idle time. This is seen as a decrease in both deliveries per hour and distance vehicles transport the loads. Decreasing the distance the vehicles transport their loads increases idle time 6.7

$$\begin{aligned}\text{Idle} = {} & 14.838 - 42.266*\text{Veh}_T^2 + 43.437*\text{Veh}_T^3 - 19.022*\text{Veh}_T^4 \\ & + 3.033*\text{Veh}_T - 0.006*\text{Veh}_T*\text{TrackB} - 0.116*\text{Veh}_T*\text{Del}_T \\ & + 0.006*\text{Del}_T - 0.035*\text{Lu}_T*\text{TrackC} - 0.021*\text{Veh}_T*\text{Seg} \\ & - 0.319*\text{Del}_T*\text{Seg} - 0.045*\text{Veh}_T*\text{Long} + 0.018*\text{Seg}_T*\text{Long} \\ & + 0.029*\text{Seg}_T*\text{Short} + 0.014*\text{Veh}_T*\text{TrackA} + 0.015*\text{Seg}_T*\text{TrackC}.\end{aligned}$$

Seg_T = Segment Size (Transformed)
Del_T = Deliveries Per Hour (Transformed)
Lu_T = Load/Unload Time (Transformed)
Veh_T = Number of Extra Vehicles (Transformed)
Short= Short Delivery Distance
Long = Long Delivery Distance

NOTE: All continuous variables were transformed before running the model. See Appendix 2 for the transformation equations.

Figure 11. Idle Mathematical Model

Design Variable	Percent Effect
Deliveries Per Hour	-13.5
Segment Size	-1.2
Extra Vehicles	37.5
Load/Unload Time	5.2
Track Layout	
Remove one branch	-3.7
Remove 2nd branch	1.6
Spurs	0.1
Delivery Distance	-6.7

Table 3. Effect of design parameters on Idle model.

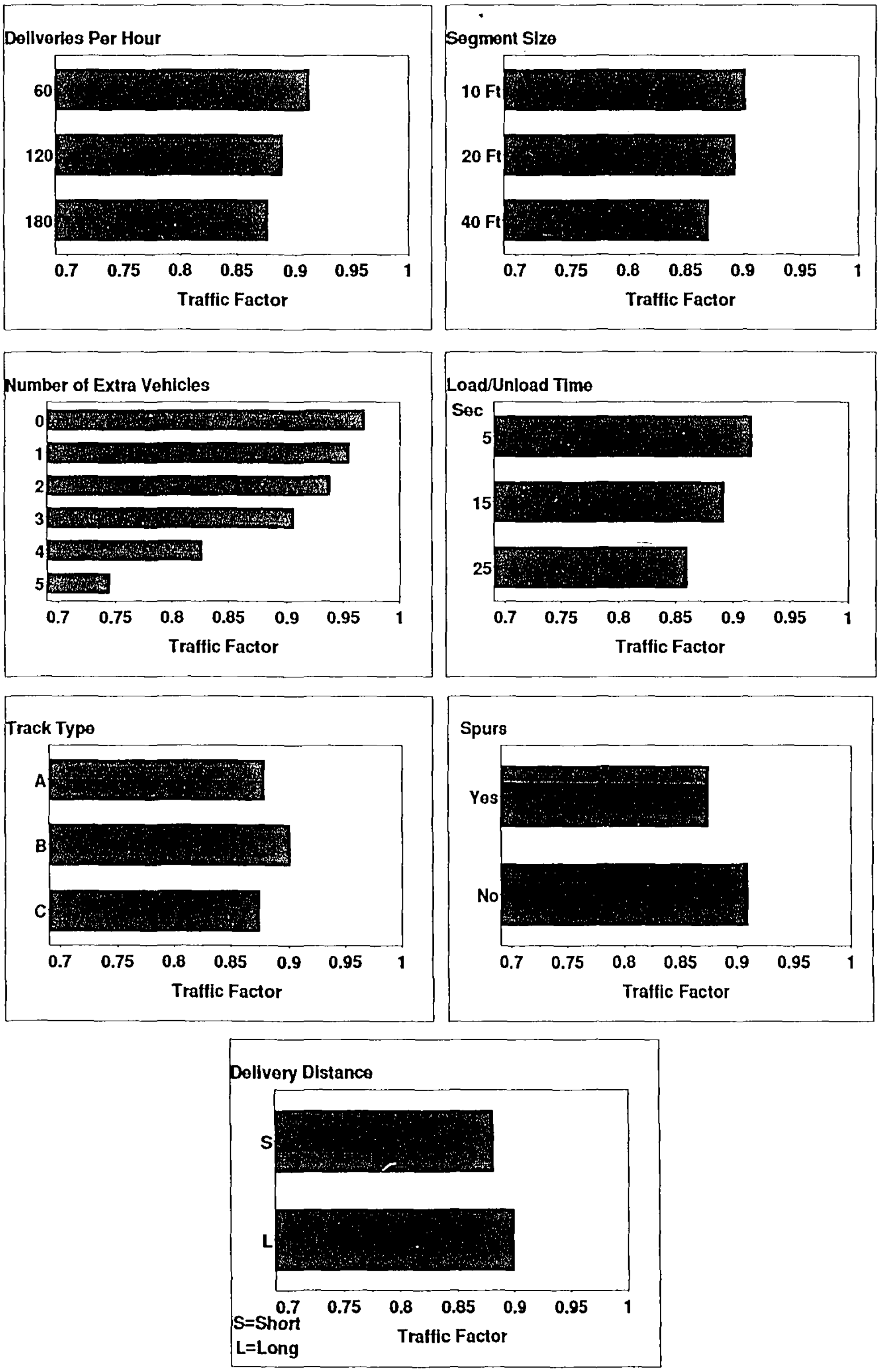

Figure 14. Traffic Factor Correlated Histograms

percent, and decreasing deliveries per hour increases idle time 13.5 percent.

Load/unload time contributes up to a 5.2 percent increase in idle time. Short load/unload times reduce vehicle blocking and time to deliver a load. Both contribute to a reduced need for vehicles, which causes an increase in idle time.

Consistent with the blocked model, removing branching segments in the layout had mixed results on the idle model. Removing the first branching segment resulted in a 3.7 percent decrease in idle time and removing the second branch resulted in a 1.6% increase. Upon closer examination of the simulation data, the initial decrease in idle time results from the vehicles in the track B facility spending more time on average traveling empty to pick up a new load. The vehicles in track C spend less time traveling empty to pick up new loads, increasing idle time. Therefore, in this facility, idle time is minimized with track B where the empty vehicle travel is greatest. Adding spurs to the track layout had no effect on the vehicle idle time.

Increasing track control segment size resulted in a 1.2 percent decrease in idle time. The idle time decrease is due to the extra blocking that occurs with large control segments.

Traffic Factor Model

SAS^R was used to develop a mathematical model for traffic factor. Figure 13 shows the model. The R-square for the model was 0.78. The correlated histograms used to make a detailed analysis of the

$$
\begin{aligned}
\text{Traffic Factor} = {} & 0.926 - 0.019*Veh_T^4 + 0.0007*Seg_T*Lu_T - 0.0245*Veh_T*TrackC \\
& - 0.018*Veh_T*TrackA + 0.074*Veh_T*Long + 0.061*Veh_T*Short \\
& - 0.012*Veh_T*Seg_T + 0.212*Seg_T*Del + 0.039*Veh_T*Del_T \\
& - 0.013*Seg_T*TrackB - 0.030*Lu_T*TrackA - 0.033*Lu_T*TrackB \\
& - 0.027*Lu_T*TrackC - 0.011*Del_T*Long - 0.010*Lu_T*Short \\
& - 0.010*Seg_T*TrackC.
\end{aligned}
$$

Seg_T = Segment Size (Transformed)
Del_T = Deliveries Per Hour (Transformed)
Lu_T = Load/Unload Time (Transformed)
Veh_T = Number of Extra Vehicles (Transformed)
Short= Short Delivery Distance
Long = Long Delivery Distance

NOTE: All continuous variables were transformed before running the model. See Appendix 2 for the transformation equations.

Figure 13. Traffic Factor Mathematical Model

Design Variable	Percent Effect
Deliveries Per Hour	-3.5
Segment Size	-3.2
Extra Vehicles	-22.2
Load/Unload Time	-5.6
Track Layout	
Remove one branch	2.2
Remove 2nd branch	-2.7
Spurs	3.5
Delivery Distance	-1.8

Table 4. Effect of design parameters on Traffic Factor model

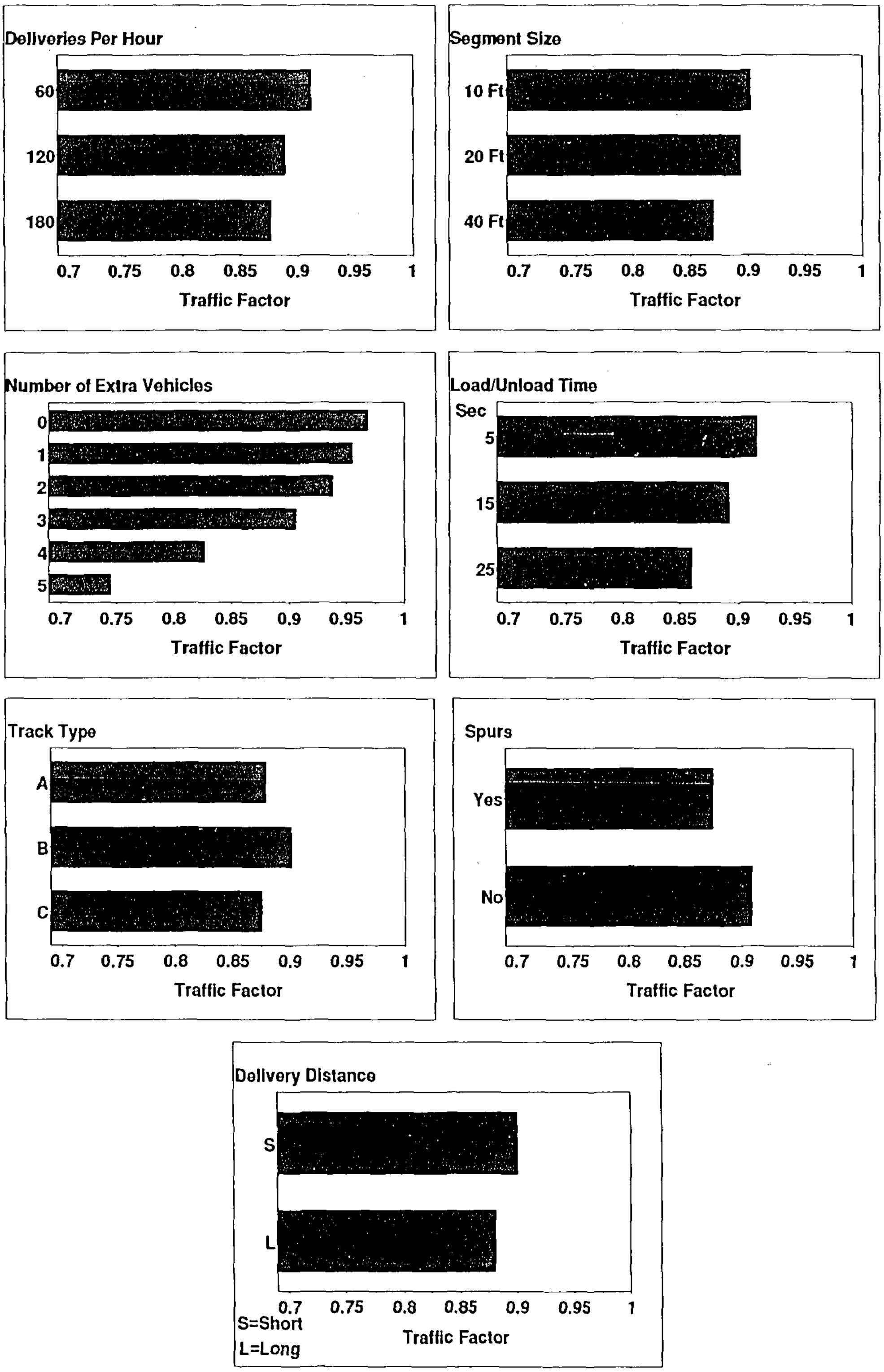

Figure 14. Traffic Factor Correlated Histograms

contributions to the traffic factor are in figure 14 and the tabulation of the results is in table 4 .

The traffic factor is calculated based on the average vehicle percent idle time and blocked time. The idle and blocked models were described in detail in the previous two sections and will be used as the basis to explain how the AGV design parameters affect the traffic factor. Examining the traffic factor equation indicates that an increase in blocked time results in a decrease in traffic factor (more congestion on the track). In addition, as idle time increases, each vehicle spends more time unproductively, resulting in a decrease in traffic factor. If idle time per vehicle goes up, but the blocked time stays constant, each vehicle will spend more time blocked per time spent productively servicing requests, thus decreasing the traffic factor.

The number of extra vehicles in the facility has the largest contribution to the traffic factor. If five extra vehicles are introduced into the facility, the traffic factor will decrease 22.2 percent. Adding the first two vehicles has a much smaller impact on traffic factor, 1.2 percent and 1.7 percent respectively. In contrast, the final two vehicles add 8 percent each. Idle time and blocked time both increase as extra vehicles were added, resulting in a decrease in the traffic factor.

Increasing the load/unload time, deliveries per hour, and segment size all decrease the traffic factor. Their contributions are 5.6, 3.5 and 3.2 percent respectively. Idle time and blocked time play opposite roles in how these three variables affect the traffic factor. Increasing load/unload time, deliveries per hour, and segment size increase blocking time while decreasing idle time. However, in all three cases, blocked time has a larger impact resulting in an overall decrease in the traffic factor.

Examining track design, the layout which maximizes traffic factor is track B. This indicates that when designing a track, putting in the maximum number of branching segments or short-cuts does not maximize the traffic factor. Comparing all three track designs, track B results in the lowest idle time and the lowest blocking time, resulting in the highest traffic factor.

The second track design parameter was load/unload spurs. Adding spurs increased traffic factor 3.5 percent. This increase results directly from less vehicle blocking since idle time was not impacted by spurs.

The final design parameter examined the influence of the delivery distances. Substantially increasing the delivery distances only decreased the traffic factor by 1.8 percent. Nearly all of this decrease results from a 6.7 decrease in idle time when long delivery distances are used. This is an indication that the material handling system will serve the factory well through future changes in the manufacturing process.

Minimizing Response Time

An important requirement in any materials handling system is to minimize the time required to respond to a material delivery request. A model was generated to determine which AGV design parameters influenced the response time to material requests. Figure 15 shows a description of the model. This model explains 70% of the variation in the data. In the model, only two variables significantly influenced the response time: the number of extra vehicles, and the number of deliveries per hour.

The number of extra vehicles had a dramatic effect on the system response time, as shown in figure 15. Adding one additional vehicle reduced the response time 14X, with subsequent vehicles having little effect on system response time.

The number of deliveries per hour had a much smaller impact on system response time. When deliveries per hour were low, system response time was greater. At first pass, this goes against common sense. However, this increase in response time was due in part to the small number of vehicles required to service the facility. Also, the distance a vehicle travels empty to pick up a load was proportionally higher when the delivery requests per hour were low.

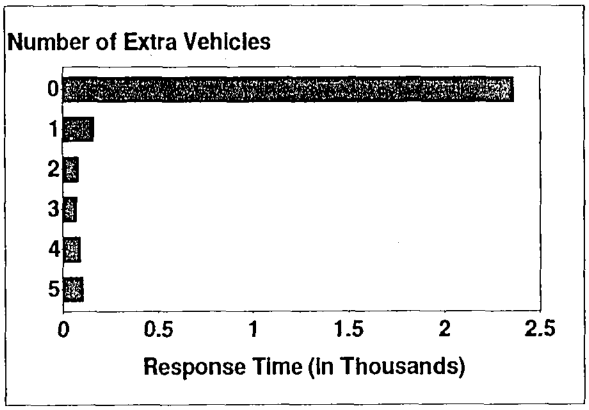

Figure 15. Response Time Correlated Histogram

$$\begin{aligned}\text{Wait} = {} & 169847.6 - 433495.8*\text{Veh}_T^2 + 410399.3*\text{Veh}_T^3 \\ & - 170841.0*\text{Veh}_T^4 + 26396.0*\text{Veh}_T + 3836.9*\text{Seg}_T*\text{Del}_T \\ & + 762.2*\text{Veh}_T*\text{Del}_T + 183.8*\text{Del}_T - 198.4*\text{Del}_T*\text{TrackA}_T.\end{aligned}$$

Seg_T = Segment Size (Transformed)
Del_T = Deliveries Per Hour (Transformed)
Veh_T = Number of Extra Vehicles (Transformed)

NOTE: All continuous variables were transformed before running the model. See Appendix 2 for the transformation equations.

Figure 16. Wait Mathematical Model

CONCLUSIONS

The goal of this project was to determine which AGV design parameters had the greatest effect on the four optimization goals:

1. Maximize the traffic factor
2. Minimize the number of vehicles
3. Minimize system response time
4. A design which is flexible for the changing production needs.

Using these optimization goals, the following five design guidelines were established based on the seven design variables (number of track branching segments, number of deliveries per hour, number of extra AGVs, material load/unload time, use of load/unload spurs, size of track control segments, and delivery distances) evaluated in this research project.

1. The number of vehicles had a significantly larger effect compared to the other design parameters. To optimize traffic factor, no extra vehicles should be placed in the factory. Adding vehicles causes increased vehicle blocking which results in lowering the traffic factor. Similarly, to minimize the number of vehicles in the factory, which reduces the cost of the material handling system, no additional vehicles should be added. Conversely, adding one additional vehicle drastically reduced the time to respond to material requests. The recommendation is to add one extra vehicle since it has a small effect on traffic factor but a dramatic effect on system response time. The cost of adding one extra

vehicle is justified by the drastic decrease in system response time.

2. Minimizing the load/unload times increased traffic factor by 5.6%. In comparison, adding load/unload spurs increased traffic factor 3.5%. In this factory, it would be more beneficial to focus on minimizing the load/unload times rather than build in spurs at each station, especially since spurs occupy valuable manufacturing floor space.

3. Designing long track segment-control zones did not have a large impact on traffic congestion. Using longer track segments provides a less expensive traffic control system and may outweigh the small increase in traffic congestion.

4. The results suggest that proper track design is critical to optimizing the AGV system. In this nine workstation facility, neither maximizing or minimizing the layout branching gave the best results. Simulation is the best way to optimize the track. Developing general track design guidelines was not possible for this facility.

5. The final goal was to build a factory which could adapt to production changes. Neither an increase in delivery distances nor an increase in material requests (deliveries per hour) had a major effect on the performance of the material handling system. All four of the layouts

evaluated could accommodate changes in the manufacturing process without substantial changes in AGVS design.

Suggestions for further research include studying how AGV systems adapt to changes in factory requirements and what can be done in the initial design phase to anticipate those changes. In addition, work needs to be done to determine the optimum method to schedule the introduction of material into the facility, either at a constant rate or based on the availability of workstations and AGVs.

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Appendix A

Simulations

The following variables were evaluated in the simulation runs:

Track Layout: Track A, Track B, Track C, and Track D
Segment Size: 10 ft, 20 ft, and 40 ft
Load/Unload Time: 5 sec, 15 sec, and 25 sec.
Deliveries per Hour: 60, 120, and 180
Delivery Distance: Short and Long
Extra Vehicles: 0, 1, 2, 3, 4, and 5.

For each of the 4 layouts, the following 14 simulations were run:

	Segment Size	Load/Unload Time	Deliveries per Hour	Delivery Distance
1.	20	15	120	Short
2.	10	15	120	Short
3.	40	15	120	Short
4.	20	5	120	Short
5	20	25	120	Short
6.	20	15	60	Short
7	20	15	180	Short
8.	20	15	120	Long
9.	10	15	120	Long
10	40	15	120	Long
11	20	5	120	Long
12	20	25	120	Long
13	20	15	60	Long
14	20	15	180	Long

Each of the 14 combinations was run with the minimum number of vehicles required to handle the delivery load and then an additional five times adding one vehicle each time.

Each simulation was repeated with a different random number seed to determine the experimental error.

A total of 672 simulations were run.

APPENDIX B

Data Transformations

All continuous variables were transformed before they were entered into SAS^R for data analysis. This was done to avoid a multicollinearity problem. The general equation for the transformation is:

$$X_T = \frac{X - \frac{\{Xmax + Xmin\}}{2}}{\frac{\{Xmax - Xmin\}}{2}}$$

This equation was used to generate the transformation equations for the specific continuous variables.

$$Del_T = \frac{Del - 120}{60}$$

$$Seg_T = \frac{Seg - 25}{15}$$

$$Lu_T = \frac{Lu - 15}{10}$$

The transformation for the number of extra vehicles was handled differently. Since the log of 'number of extra vehicles' was evaluated while developing the models, the variable 'number of extra vehicles' could not be less than or equal to zero. Therefore, +2 was added to the transformation equation. The variable, the number of extra vehicles, varied from +1 to +2 in the model.

$$\mathrm{Veh}_T = 2 + \frac{\mathrm{Veh} - 3}{3}$$

VITA

The author is the daughter of Richard and Kathryn Dick of Apple Valley, Minnesota. She was born in Kearny Arizona on July 31, 1963. Her high school education at Apple Valley High School was completed in 1981. Ms. Dick graduated with honors from the University of Minnesota in 1985 with a Bachelor of Science in Chemical Engineering, and an emphasis in polymer science.

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END

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