Potentials for bi-directional guide-path for automated guided vehicle based systems

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Most current applications of automated guided vehicle systems (AGVS) in manufacturing shop environments employ uni-directional guide-paths for vehicle routing despite the fact that bi-directional vehicles exist. In this paper comparisons and issues regarding uni-directional and bi-directional flows are presented. Also presented is a model of a bi-directional traffic flow guide-path. The effect of the traffic flow pattern on the shop throughput is demonstrated and compared to that of a uni-directional flow system of an equivalent facility. The model is implemented using computer simulation.

Introduction

The typical automated guided vehicle (AGV) system operative in today’s manufacturing facility employs a uni-directional guide-path system as shown in Fig. 1, even though bi-directional vehicles are in existence (Barrett Electronic Corp., 1981, Material Handling Institute 1980, Maxwell and Muckstadt 1982, Raymond Corp., 1980). One of the justifications for the use of uni-directional flows is its simplicity in design and control. Whereas the use of uni-directional flow may be justified for complex systems that employ a large number of vehicles, the use of uni-directional flow for simple systems (i.e. systems using few vehicles) may in several cases not be appropriate, control difficulties notwithstanding. In simple systems, the gain in productivity that results in the use of bi-directional flow can easily compensate for the added cost in acquiring better control softwares and/or intelligent vehicles that make bi-directional flow possible. The fact that the advantages of employing bi-directional flow as opposed to all uni-directional flows have been well documented in other traffic flow systems—highways, streets, and railroads—(Agent and Clark 1982, Frank 1966, Petersen 1974, Weingarten 1958) make it all the more important to investigate the potentials of bi-directional AGV systems and to take a critical look at the current standard of employing uni-directional flows. Furthermore, as technological improvements are made in software development and in vehicle design, perhaps the use of the trackless system or the free ranging vehicles (Premi and Besant 1983) may become even more promising for simple systems than the bi-directional flow systems, and much more so than the uni-directional case.

In this paper, guide-path system design strategies for bi-directional flows are discussed, along with related problems or weaknesses associated with each design. A

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model of traffic flow and control is also presented. Finally, using examples, comparisons are made between the productive potentials of some facilities when operated either on a uni-directional mode or bi-directional mode.

**Layout and design of a guide-path**

In automated guided vehicle based system, the layout and the orientation of the guide-wire system dictate the direction of traffic flow in any given aisle as well as the traffic intensity in each aisle. In the design of a bi-directional guide-path system, one of several layout and guide-wire orientation alternatives can be adopted. These alternatives include the following:

*Case 1:* Have parallel wire tracks with reverse orientation on each aisle.

*Case 2:* Have a single switchable wire-track on each aisle. The switching of the guide-path is dependent on the flow demand.

*Case 3:* Have a mixed guide-path that is comprised of both uni-directional and bi-directional aisles, with bi-directional flows allowed only on selected aisles.

*Case 1: Parallel tracks on each aisle*

If the guide-path shown in Fig. 1 was to be designed using parallel uni-directional wire tracks on each aisle, its equivalent can be represented as shown in Fig. 2. The design concept employed here is very similar to that used for major highways. AGV systems employing this type of layout to permit bi-directional flow do so only in superficial form. Except at points of intersection, the guide-path system is
essentially uni-directional. With sufficient clearance space left between parallel tracks, there is virtually no interference between vehicles on the same aisle and travelling in opposite directions.

There are obvious advantages and disadvantages to this design. Unlike the uni-directional case, the distance travelled by vehicles in moving between points is reduced, assuming the layout is not symmetric. Consequently, this should improve the response time of the vehicles. On the other hand, there is a lack of space economy in this design. Aisles are required to be wide enough to allow two vehicles to pass side by side. Depending on the size of the guide-path system, investment on the guide wire could be high. Most importantly is the problem of traffic control at intersections. For a uni-directional system, only two turns or interchange ramps are required at intersections, assuming movements are permitted only along coordinate axes. For a bi-directional flow network, if all turns are permitted, eight interchange ramps are required as shown in Fig. 3 (Irving et al. 1978). The cost of acquiring a control software to manage intersection activities could be high. Such software must posses sufficient versatility to handle all anticipated vehicular conflicts at the intersections.

Case 2: Single switchable track

The single switchable track design is similar to the concept of reversible streets (Agent and Clark 1982, Kavanaug and Dekay 1959, Weingarten 1958) or single railroad tracks between terminals (Dube and Belshaw 1978, Frank 1966, Petersen 1974, 1975, 1977). If the guide-path of Fig. 1 is redesigned to that of a bi-directional,
single track system, the resultant system can be represented as in Fig. 4. For each wire segment or aisle between intersections, traffic flow takes place in either direction. However, each aisle segment operates as a gate (open and close) or switch (on and off). If flow signal is being transmitted to one direction, a signal in the reverse direction is automatically turned off or ineffective. Thus, vehicles are allowed to travel in one direction at any time. This type of bi-directional flow presents highly challenging traffic control problems. Not only does the system controller have to contend with difficult intersection control problems, but also with vehicle inter-
Figure 4. A single track bi-directional guide-path.

ferences within the aisles. It requires also the designation of temporal vehicle buffering areas throughout the guide-path to hold blocked vehicles. The number of buffering areas designated to hold blocked vehicles and their holding capacities are themselves decision variables that depend on the applicable vehicle fleet size, vehicle routing strategy, guide-path layout, and facility size.

From implementation point of view, a sophisticated control software is required to operate the system. Adoption of this design strategy should be based on a thorough economic analysis.

Case 3: Mixed design

This design combines the characteristics of uni-directional and bi-directional systems. Some aisles of the guide-path system are operated on a bi-directional mode while the rest operate strictly on a uni-directional mode. Less used aisles are candidates for bi-directional flows, using either the strategy of cases 1 or 2 or a combination of the two bi-directional designs.

At present, none of the three bi-directional flow designs described is implemented on a wide scale in actual industrial settings. As mentioned before, most AGV systems operational today employ uni-directional flows. There seems to be a reluctance to move toward bi-directional AGV systems despite the early and widespread applications of both methods of flows in highway and railroad systems (Dube and Belshaw 1978, Frank 1966, Petersen 1974, 1975, 1977). City planners have long understood the need to designate streets as one-way or two-ways depending on the expected traffic flow volume, system throughput, safety and other economic and political reasons (Agent and Clark 1982, Kavanau and DeKay 1959, Weingarten
Railroads are characterized by single and double track segments to improve system performance (Dube and Belshaw 1978, Petersen 1975, 1977). Although, there are obvious differences in the operation and environmental requirements of the typical street traffic, with proper guide-path layout design, improvement in vehicle intelligence and controller sophistication and versatility, AGV systems can also be made to benefit from bi-directional flows.

With bi-directional flow systems briefly described, subsequent discussions and the traffic flow model presented in this paper will assume the case 2 bi-directional flow design.

**Single tract bi-directional flow network**

The bi-directional guide-path of Fig. 4 can be modelled as a network as shown in Fig. 5. The network nodes represent the guide-path intersection points (i.e. crossings, merges, diverges, and pickup/delivery points) while the segments represent the aisles. By specifying the nodes that bound a segment, the segment is uniquely defined. However, since in a bi-directional network two-way traffic is permitted, traffic reference in a particular segment must specify the direction of flow. For example, if $\alpha$ and $\beta$ are adjacent nodes and traffic flow is from node $\alpha$ to $\beta$, traffic reference in that segment will be viewed as travelling in arc $(\alpha, \beta)$ while flows in the reverse direction will be referenced as being in arc $(\beta, \alpha)$. For point location and vehicle tracking, the model uses the cartesian coordinate system. Therefore, for every node $\alpha$, a point location is provided by specifying the coordinates $(X_\alpha, Y_\alpha, Z_\alpha)$.

![Figure 5. A single track bi-directional guide-path model.](image-url)
However, for the materials presented in this paper, all nodes are assumed to lie on the same horizontal plane. As a result, the use of the Z-axis coordinate will be discontinued in subsequent sections of the paper.

The traffic flow model
In modelling the flow of vehicles in the network, the following assumptions are made:

(a) Arcs enter and leave nodes only along the x and y-axes.

(b) Only rectilinear (i.e. 'L') and euclidean (i.e. 'T') shaped arcs are allowed in the network. All other shapes, including 'U' shapes are not permitted.

(c) A maximum of four arcs can converge at a node.

(d) Vehicles are not permitted to make sharp turns. All turns are negotiated through interchange ramps as shown in Fig. 6.

(e) The points where a ramp diverges from one arc and merges with another are equidistant to the centre of the node the ramp serves. The same assumption holds for ramps that approximate turns within 'L' shaped arcs.

(f) All vehicles travel at the same speed.

(g) All nodes have facilities for buffering or holding blocked vehicles. The location and implications of buffering facilities are discussed later in this paper.

In addition to other network features, Fig. 6 also shows the concept of check zones and check points (Egbelu and Tanchoo 1982, 1984). A check zone is a constrained region around a node and is not permitted to accommodate more than one vehicle at

Figure 6. A section of a guide-path network.
a time. These zones are designed to facilitate traffic control and to ensure safe, collision free, and un-obstructed intersections. On the other hand, the point where an arc enters a check zone defines a check point (Egbelu and Tancho 1982, 1984). Check points are decision points for vehicles in transit. Such decisions include holding, turning, right of way, etc. The concepts of check points and check zones facilitates the control of vehicles and also their monitoring. Thus, from discrete simulation view point, the movement of a vehicle from a source node to a destination node can be modelled as consisting of discrete jumps from the check point of one node to that of another. The actual jump time is a function of (1) the travelling speed of the vehicle, (2) the distance between the check points of the adjacent nodes, and (3) the traffic condition on the aisle (i.e. arc) to be travelled. Suppose $V_1$ represents a vehicle to travel in arc $(x, \beta)$. The effect of traffic condition within arc $(x, \beta)$ on the travel time of $V_1$ depends on whether there is currently any vehicles in arc $(x, \beta)$ to impede its (i.e. $V_1$) movement or there are vehicles travelling in arc $(\beta, x)$ (i.e. reverse direction of arc $(x, \beta)$).

Suppose $x$ and $\beta$ are adjacent nodes and a vehicle is planned to travel in arc $(x, \beta)$. As shown in Egbelu and Tancho 1982, 1984), the distance between the check

\[
\begin{aligned}
&= \left\{ 
\begin{array}{ll}
(X_x - X_\beta)^2 + (Y_x - Y_\beta)^2 + (f - 2e)\phi, & \text{if the distance from } x \text{ to } \beta \text{ is euclidean} \\
X_x - X_\beta + Y_x - Y_\beta + (f - 2e)(\phi + 1), & \text{if the distance from } x \text{ to } \beta \text{ is rectilinear}
\end{array}
\right.
\end{aligned}
\]  

(1)

where $\phi = 1$, if a turn is required at $x$ to reach $\beta$, or 0, otherwise; $f =$ length of an interchange ramp and $e =$ the distance between a check point and the centre of the node it serves. This factor is also used in adjusting for the actual length of a rectilinear arc as diagrammed in Fig. 6.

In modelling the traffic flow in the system, consideration must be given to the form of vehicle routing to be implemented. Basically, two routing options are available, namely, static routing and dynamic routing. In static routing, the path between any two points in the network is predefined. On the other hand, in the dynamic case, the exact travel route is not known ahead of time until the journey is fathomed. Under this routing approach, a selected path is only tentative and is subject to re-evaluation every time the vehicle arrives at a node point. A new path could be selected as a result of the re-evaluation. In this study, only static vehicle routing option is considered.

With the path determination decision made, vehicle routing involves monitoring and controlling vehicle movement as it traverses through its path. Since the movement of a vehicle from its source node to its destination node involves passage through the nodes along the path, estimates of arrival times at the nodes (or check points) must be made. If $x$ and $\beta$ are adjacent nodes with traffic flow in the direction of $x$ to $\beta$, and if $T'$ denotes the estimate of the arrival time at node $\beta$ given that the vehicle was at node $x$ at time $T$, then from Egbelu and Tancho 1982

\[
T' = \max \{ T + dx\beta/S_x + \omega \dot{x}, T_1 + t_1 \}
\]  

(2)

where $x$ and $\beta$ denote the nodes that bound arc $(x, \beta)$ and arc $(x, \beta)$ is the next arc to which vehicle V is to be routed. $T$ is current time or the time vehicle V is to be routed to arc $(x, \beta)$, and $dx\beta =$ length of arc $(x, \beta)$. $\omega$ is estimate of the additional time required to move a vehicle from a buffer area to the main track or aisle. $\dot{x} = 1$, if vehicle is in buffer area or 0, otherwise. $T_1$ is the estimated time the last vehicle currently in arc $(x, \beta)$ and travelling immediately ahead of vehicle V is scheduled to
arrive at the check point of node $\beta$. If there is no vehicle currently in arc $(\alpha, \beta)$, then $T_1=0$. $t_\epsilon$ is the time required to travel the minimum headway separation distance between adjacent vehicles. If $T_1=0$, then $t_\epsilon=0$ and the estimated arrival time reduces to

$$T'' = T + d\alpha \beta \frac{1}{S_\epsilon} + \omega \lambda$$

(3)

Equations (1)–(3) are used in routing and calculating the expected arrival times of vehicles at various network segments in the simulation model for the AGV system.

Routing through an intersection

Compared to uni-directional networks, more complex algorithms are required to route and control vehicles through intersections in a bi-directional network. Although several rules can be implemented to control intersections (Egbelu and Tanchoco 1982), only one possibility is considered in this paper. For the discussions that follow, both notational and graphical representations are employed where appropriate to clarify the issues raised.

The intersection control algorithm employed is simple and operates as follows. Suppose Fig. 7 represents a traffic scenario. The $\alpha$'s denote node labels. $V_1$ is a vehicle travelling in arc $(\alpha_1, \alpha_0)$ and to continue in arc $(\alpha_0, \alpha_2)$ after crossing node $\alpha_0$. Currently $V_1$ is at the check point of node $\alpha_0$. Since there is no interference from other vehicles due to their lack of presence around node $\alpha_0$, the control requirement to route $V_1$ to arc $(\alpha_0, \alpha_2)$ through the intersection is minimal and trivial. The projected arrival time of the vehicle at $\alpha_2$ is calculated using eqns (1) and (2) or (1) and (3) as the scenario may call for.

In the order of increasing complexity, suppose the scenario changes to that of Fig. 8. Vehicles $V_1$ and $V_2$ arrived at the check point of node $\alpha_0$ almost at the same time (i.e. the time interval between the arrivals of the two vehicles at the check point

![Figure 7. One-vehicle intersection crossing scenario.](image-url)
of node $x_0$ is sufficiently small that none of the two vehicles can successfully cross the node without interfering the movement of the other vehicle. If $V_1$ is transferring to any arc other than arc $(x_0, x_1)$ and $V_2$ is transferring to any arc other than arc $(x_0, x_4)$, again the routing problem is trivial. The two vehicles are routed sequentially through the node. The order of routing can be determined using an appropriate rule. A second case would be if say $V_1$ is to transfer to arc $(x_0, x_1)$ and $V_2$ is to continue on arc $(x_0, x_2)$ or arc $(x_0, x_3)$. Regardless of the position of $V_2$ in arc $(x_4, x_0)$, vehicle $V_1$ is held in arc $(x_4, x_0)$ until $V_2$ passes. Thereafter, $V_1$ enters arc $(x_0, x_1)$ to continue on its journey. All other similar cases of vehicle interference involving two vehicles are resolved in the same manner. On the other hand, suppose the scenario of Fig. 8 is such that vehicle $V_1$ requires to continue in arc $(x_0, x_1)$ after crossing node $x_0$ and vehicle $V_2$ requires to continue in arc $(x_0, x_4)$ also after crossing node $x_0$. A deadlock situation exists.

To resolve the deadlock, one of the vehicles is selected for buffering. The buffering of one vehicle clears the track for the passage of the other. Thereafter, the buffered vehicle is released back into the main track to continue its journey.

A more difficult intersection control problem arises when vehicles or strings of vehicles approach an intersection from three or four directions as shown in Figs 9 (a) and 9 (b). In these cases, the control algorithm selectively buffers some of the vehicles, gradually reducing the scenario to a two vehicle interference problem as previously discussed. Thereafter, the buffered vehicles are selectively released into the track to resume their trips according to their predefined paths.

One of several algorithms can be employed to resolve the kind of conflicts portrayed in Figs 9 (a) and 9 (b). In this study, the implemented algorithm is given in the Appendix. There are major assumptions in the algorithm. Firstly, it is assumed that all nodes have buffers and that the buffers are of infinite capacity. Furthermore, it is assumed that the time required for a vehicle to steer into and out of the buffer is small compared to the overall travel time required. Thus, the elapsed time required to enter and exit a buffer is negligible.
Designation of buffering areas for vehicles in transit

One of the operational problems to contend with in a bi-directional network is how to resolve vehicular conflicts in the use of an aisle. Such conflicts generally arise when two sets of vehicles travelling in reverse directions desire to use an aisle. This implies there is simultaneous demand for arc $(\alpha, \beta)$ and arc $(\beta, \alpha)$ where $\alpha$ and $\beta$ denote node labels. As stated previously, the use of arc $(\alpha, \beta)$ automatically disables arc $(\beta, \alpha)$ by design and vice-versa. By earlier discussion, the conflict is resolved by holding one set of vehicles in a buffering area while giving the other set the right of way. Mention has been repeatedly made of vehicle buffering areas in this paper without addressing...
the problem of location and design of such areas. The location and design problems are now addressed.

In a plant environment, the location and design of vehicle buffering areas require a compromise of several factors, among which include space economy, design simplicity, ease of vehicle control, and investment on guide wire and control system. One of the earliest design decisions that should be addressed is the number of nodes in the network that should have buffering facilities. The two extreme cases, are to have a buffering facility at every node or to have only one central buffering facility. For a known fleet size, the more facilities available, the smaller the capacity requirement of each facility and vice-versa. Designation of buffering facilities at every node implies an increased demand on floor space and consequently an increase in investment on building and guide wire acquisition. The advantage of having buffering facility at every node is realized through simplicity in traffic control.

Alternatively, buffering facilities could be provided only at selected intersections. This reduces the space requirement problem. It does, however, imply that traffic conflict resolutions at nodes with no buffering facilities may require, temporarily, routing some of the affected vehicles to another arc or one of the buffering facilities in the selected nodes. Under this design, vehicles may be routed backward where necessary. Depending on the number of vehicles to be routed backward at any instance and the level of traffic congestion in the network, backward routing may produce serious traffic control problems. Conflict in one arc can set up a chain of conflicts downstream through propagation. The task placed on the system controller is high in a case of this nature.

**Design of buffering areas**

Requirements for a good design of a buffering area includes accessibility, space economy, minimum interference between vehicles in the area, and minimum investment on guide wire control systems. Three different designs have been suggested in this paper, namely, loop, siding, and spur designs. Each of these designs is briefly described below. The author acknowledges other design alternatives not addressed here.

*Loop design:* The features of the loop design are two uni-directional loops per each aisle and located at the ends of the aisle. In other words, if \( x \) and \( \beta \) are adjacent nodes, one loop is dedicated for buffering vehicles travelling in arc \((x, \beta)\) in case of conflict and the other is used for buffering vehicles travelling in the direction of arc \((\beta, x)\). Therefore, the number of buffering facilities required at a node point is equal to the number of directions vehicles can enter the node. This design when diagrammed can be represented as shown in Fig. 10.

*Siding design:* The features of the siding design type of buffer are shown in Fig. 11. It includes a uni-directional siding at each end of an aisle close to the end nodes. A siding serves vehicles travelling only in its direction of orientation.

The concept of sidings to support traffic flows has been well practiced in the railroad industry. The major difference, however, is in the locations of the sidings and the frequency of occurrence along any track segment. Due to the macro nature of the railroad system compared to the AGV system, railroad track segments require several sidings along any segment. The actual number of sidings along any track segment is a function of track length, traffic intensity, mix of carriers that use the line, and carrier travel speeds (Dube and Belshaw 1978, Petersen 1974, 1975).
Spur design: The spur design is characterized by dead end spurs as depicted in Fig. 12. These spurs are capable of being excited in either direction. Again, like the loop and siding designs, two spurs feature on each aisle, close to the end nodes. A spur serves vehicles travelling in only one direction. However, unlike the other two designs, vehicles entering into a spur will depart according to the last in–first out (LIFO) rule.

In all three cases of buffer design discussed above, it may be possible to accomplish the designs with a small additional investment in guide wire since there are vehicles available in the market today that are capable of leaving the main track temporarily to some off location, a short distance away from the track. After accomplishing their tasks at the off location, the vehicles can easily return to the main track to continue their trips.

Comparison of bi-direction and uni-directional flows

In the design of AGV system, most designers automatically discount any consideration of bi-directional flow without in-depth analysis, even when traffic control problems would not be significantly affected. However, if all initial biases were to be laid aside, it can be demonstrated that some facilities presently utilizing
uni-directional flows could have benefited significantly if bi-directional flows were considered appropriately, control difficulties notwithstanding. Therefore, one of the initial decisions to be made in the design of an AGV system is to determine whether bi-directional or uni-directional flow is appropriate. Thorough analysis is required to arrive at this decision. Simulation technique is particularly useful in this regard. It has been pointed out repeatedly that simulation seems to be the only available tool for analysing complex material handling problems (Maxwell 1981, Philips 1980).

In this study, the application of the simulation package AGVSim (Egbelu and Tanchoo 1983) was used for generating the kind of data required by an analyst to undertake a proper evaluation of the two routing strategies for a given facility design project. Two facilities are employed here for illustration. The layouts of the facilities when operated under uni-directional and bi-directional modes are as shown in Figs 13 and 14. Bi-directional operation simply implies an undirected network of the same layout. Notice that in each of the facility layouts, some of the track segments required in the uni-directional systems are not required in the bi-directional system. There is a reduction in both aisle space requirement and guide wire requirement. These benefits must be incorporated into any economic comparison of the two flow alternatives. This study, however, assumes the availability of buffering facilities at every node.
Figure 12. A network section showing spur design buffers.

Figure 13. Network layout for facility number 1. (a) bi-directional network, (b) unidirectional network. ——— = AGVS guide-path, D = delivery station, P = pickup station, □ = vehicle staging area.
Each of the facilities is a multi-job processing shop. Each job type has its own predefined route. Jobs intermittently arrive at the shop in predefined lot sizes. An arriving job is composed of one or more unit loads. Thus, unit loads of jobs rather than whole jobs circulate through the shop. Because of the large input data required by AGVSim, full presentation of the data employed in the simulation is difficult to package for inclusion in this paper. However, the data is available to any interested reader upon request. The primary criterion used in the comparison of the two flow alternatives is the number of unit loads completed over a period of time. Data on vehicle utilization is provided simply as supporting information.

The initial interest in the simulation was to investigate how an equal number of vehicles affect the throughput of the shops (i.e. the number of unit loads completed over the simulation period) when operated in uni-directional and bi-directional modes. In other words, given the same number of vehicles, what are the throughputs of the shops if they are operated on bi-directional flow mode as against uni-directional flow mode? To answer this question, the facilities were simulated under four different levels of vehicles.

The results of the simulation experiments for facility No. 1 are contained in Table 1 (a). For example, using nine vehicles in facility 1, a total of 1531 unit loads were completed during the simulation time when uni-directional flow was used as against an output of 2453 unit loads under bi-directional flow. There is a margin of difference of 922 unit loads. The Table demonstrates an obvious domination of the bi-directional flow layout over the uni-directional layout in all four levels of testing. Although the margin of difference in system output is high at all test levels, this margin decreases as the number of vehicles increases. This is understandable since larger fleet sizes imply more interference among vehicles.

Table 1 (b) is a quantification of the percentage improvement in system output if bi-directional flow is used in place of uni-directional flow. The percentage improve-
Table 1. (a) Shop throughput in unit loads, facility 1 (UD = uni-directional; BD = bi-directional). (b) Percentage increase in shop throughput. Using bi-directional flow over uni-directional flow, facility 1. (c) Average percentage utilization per vehicle, facility 1.

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(a)

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(b)

| Percentage increase | 99.42 | 86.08 | 74.14 | 60.22 |

(c)

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Table 1. (a) Shop throughput in unit loads, facility 1 (UD = uni-directional; BD = bi-directional). (b) Percentage increase in shop throughput. Using bi-directional flow over uni-directional flow, facility 1. (c) Average percentage utilization per vehicle, facility 1.

ment range from 60.22% under a test level of nine vehicles to 99.42% under a test level of six vehicles. Perhaps of interest also, is the fact that the higher system throughput under bi-directional application is achieved even at a slightly lower average utilization of vehicles at all four levels. Table 1(c) gives the average utilization of each vehicle during the 80 hours of simulation time. Vehicle utilization is computed based on the total time a vehicle is engaged in missions, regardless of whether it travels loaded or not.

Similarly, Tables 2(a), 2(b), and 2(c) present the results obtained when facility No. 2 was simulated also for 80 hours. Again, the differences in system output levels under the different operating modes are significant, ranging from 32.92% increase with six vehicles to 66.55% with three vehicles.

As the reader may recognize from Tables 1(b) and 2(b), there is a significant difference in performance improvement obtainable from facility 1 when compared to that from facility 2. Whereas in facility 1, an improvement range of 60.22–99.42% was obtained, only 32.92–66.55% range was obtained from facility 2. The benefits of
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(a)

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</table>

(c)

Table 2. (a) Shop throughput in unit loads, facility 2 (UD = uni-directional; BD = bi-directional). (b) Percentage increase in shop throughput when bi-directional flow is used over uni-directional flow, facility 2. (c) Average percentage utilization per vehicle, facility 2.

Bi-directional flow is felt more so in facility 1 than in 2. The differences in gains can be attributed partly to the following factors in the characteristics of the two shops:

(a) There is a higher percentage reduction in guide path size and complexity in Fig. 13 (i.e. facility 1) than in Fig. 14 (i.e. facility 2) when both facilities are converted from unidirectional to bidirectional traffic flows. In Fig. 13, the elimination of the guide path loops around departments 2, 3, 5, and 7 represent far more percentage reduction to the total layout than the elimination in Fig. 14 of loops around departments 1 and 8.

(b) The conversion of the networks from uni-directional to bi-directional flows more significantly altered the shape of the layout in facility 1 than 2.

(c) There is significantly more network intersections in Fig. 14 than in Fig. 13. More intersections would encourage more vehicle interferences.

The fact that the shop characteristics affect the percentage improvement makes it all the more necessary to analyse each system design case individually since global interpretation of result is difficult at this time without a classification of system layouts and attributes. Classification of system layouts will also help in identifying
network segments that are good candidates for bi-directional operations for those systems where completely bi-directional or uni-directional flows are not justified. Selection of segments for uni-directional or bi-directional operation must consider several factors, including:

(a) The traffic flow intensity through the segment.
(b) Traffic control requirements.
(c) Traffic load that would be imposed on other network segments (i.e. the effect of flow on other sections of the network by converting from bi-directional to uni-directional and vice-versa).
(d) Savings or increase in total travel distance over a period of time by designating a segment to operate either on a bi-directional or uni-directional mode.
(e) Future flow requirements and possible expansion or contraction of the network.

Thus, given the network of Fig. 13 and, if there is need for a mixed layout design, the network loops around departments 2, 3, 5 and 7 can be eliminated and then have the segments leading to the pickup and delivery stations of these departments operate on a bi-directional mode while other segments are operated on uni-directional mode. Such modification will obviously reduce the total travel distance through the network and this will introduce virtually no changes in flow intensity to other portions of the network. Elimination of the loops around departments 1 and 8 in Fig. 14 and replacing them with bi-directional segments leading to the pickup and delivery stations of these departments will also have similar effect in facility 2.

The second type of analysis undertaken in the study was to determine the number of vehicles required under each operating mode (i.e. uni-directional versus bi-directional) to meet targeted output levels over a fixed time period. To reduce additional computing effort, the target levels were set at 2066, 2246, 2384, and 2453 for facility 1 and 1449, 1889, 2217, and 2233 for facility 2 respectively. Notice that these target values correspond to the outputs generated and shown in Tables 1(a) and 2(a) under bi-directional operating mode. This analysis, therefore, breaks down to determining the vehicle requirements to match the targeted production levels when uni-directional flow is used. For facility 1, the results of the simulation is shown in Table 3. Notice that 13 vehicles are required to meet a production target of 2066 unit loads for the uni-directional system as against six vehicles in bi-directional system. The additional seven vehicles required for the uni-directional system represent a substantial increase in investment. It is even worse for the case of 2453 output target. Here, 11 additional vehicles are required by the uni-directional system. Table 4 also shows the differential vehicle requirement for facility 2. Like the first facility, the second facility also showed significant differences in vehicle requirement under the two operating modes.

The above results suggest the potential for bi-directional traffic flow AGV systems. Since a commonly given reason for not adopting bi-directional flow network by vendors is the difficulty of control and the cost of developing such control system, the simulation results would suggest saving in investment cost by customers even if the cost for the development of such control system is passed on and distributed to customers. Besides, customers also realize additional savings in guide wire investment due to reduction in network.
<table>
<thead>
<tr>
<th>Traffic flow pattern</th>
<th>Output target (unit loads)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2066 2246 2384 2453</td>
</tr>
<tr>
<td>UD</td>
<td>13† 16‡ 19‡ 21‡</td>
</tr>
<tr>
<td>BD</td>
<td>6 7 8 9</td>
</tr>
</tbody>
</table>

† The output obtained by the 13 vehicles was six unit loads short of the targeted output but sufficiently close to be assumed equal to the targeted output of 2066. In practise, 14 vehicles are required.‡ The actual output due to these vehicles exceeds the actual target. It is not possible to meet target with integer number of vehicles.

Table 3. Number of vehicles to meet target output levels.

<table>
<thead>
<tr>
<th>Traffic flow pattern</th>
<th>Output target (unit loads)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1449 1889 2217 2233</td>
</tr>
<tr>
<td>UD</td>
<td>6‡ 7‡ 9‡ 10†</td>
</tr>
<tr>
<td>BD</td>
<td>3 4 5 6</td>
</tr>
</tbody>
</table>

† 10 vehicles produced six unit loads less from the target but sufficiently close in this study to be neglected. Otherwise, 11 vehicles are required.‡ The actual output by this number of vehicles exceed the actual target. That is, it is not possible to meet target with integer number of vehicles.

Table 4. Number of vehicles required to meet target output levels.

The final investigation undertaken in this study was to determine the length of time it takes to achieve an output target if the same number of vehicles were used when the facilities were operated in uni-directional mode as against bi-directional mode. Again, the same output targets used in the previous experiment were used here.

The results of the experiments are as shown in Tables 5 and 6. Table 5 applies to the first facility while Table 6 applies to the second facility. The results of these experiments re-confirm that of Tables 3 and 4. In both shops, there are substantial savings in total time in operating the shops under bi-directional mode as against uni-directional mode. For example, in the first facility, whereas it requires 80 hours to meet a production of 2066 unit loads by six vehicles operating in bi-directional mode, this time increases to 158:75 hours in the uni-directional mode. For a production target of 2453 unit loads in 80 hours under bi-directional mode, this time increases to 127:80 hours when operated in uni-directional mode and using nine vehicles. As shown in the Tables, the time savings range from 47:80 hours to 78:75 hours for the first facility based on the four levels of vehicle fleet sizes tested and 27:33 hours to 55:39 hours for the second facility. These time savings can be easily translated to savings in cost to facilitate adequate economic analysis of the alternative modes during any system design project.
Bi-directional guide-path for guided vehicle based systems

<table>
<thead>
<tr>
<th>Traffic flow pattern</th>
<th>Output target (unit loads)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2066</td>
</tr>
<tr>
<td></td>
<td>(a)</td>
</tr>
<tr>
<td>UD</td>
<td>158.75</td>
</tr>
<tr>
<td>BD</td>
<td>80.00</td>
</tr>
</tbody>
</table>

Table 5. Time to produce output target using equal number of vehicles \((a) = \text{time in hours}, (b) = \text{number of vehicles used})

<table>
<thead>
<tr>
<th>Traffic flow pattern</th>
<th>Output target (unit loads)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1449</td>
</tr>
<tr>
<td></td>
<td>(a)</td>
</tr>
<tr>
<td>UD</td>
<td>135.39</td>
</tr>
<tr>
<td>BD</td>
<td>80.00</td>
</tr>
</tbody>
</table>

Table 6. Time to produce output target using equal number of vehicles \((a) = \text{time in hours}, (b) = \text{number of vehicles used})

Conclusion

A model that describes the flow and control of AGVs in a bi-directional network is presented. Using simulation technique, it was demonstrated that the use of a bi-directional traffic flow network can lead to an increased productivity in some AGV system installations, especially those that require few vehicles. The results obtained are very useful from a design point of view. For a fixed workload, the number of vehicles required to achieve a certain transport capacity under bi-directional and uni-directional flows can be easily determined. This provides a basis for economic analysis to determine if the acquisition of additional traffic control capability and/or more intelligent vehicles is justifiable.

Since a large number of uni-directional AGV installations today have fewer than 10 vehicles in use, a good percentage of these could have realized potential savings through reduction in vehicle fleet size if bi-directional flows were initially considered. When analysed in the context of bi-directional flows, many of the current systems may indicate some over design. Although network control is by far more difficult in a bi-directional system than in a uni-directional system, it is recommended that system planners evaluate both flow options carefully before adopting a strategy.

Appendix

In the algorithm presented here, a vehicle is said to arrive at a node if it came from a preceding node or exiting from a buffer of the node to the main track to resume its journey. Also, interferences between vehicles at node points are classified as major conflict and minor conflict. A conflict between two vehicles \(V_1\) and \(V_2\) at a node is called a major conflict if \(V_2\) is blocked from entering an arc because \(V_1\) is travelling in
the same arc but in opposite direction and vice-versa. A conflict is classified minor if there is interference only in crossing the node point. In other words, the vehicles do not block each other's way except that it is not possible to route either of the vehicles through the node without interfering the flows of the vehicles unless one of them is held for some time or slowed. The 'current' vehicle in the algorithm refers to the vehicle that arrives at the node. Where two or more vehicles arrive simultaneously at a node from different arcs, the first queried vehicle is taken to be the first to arrive.

The conflict resolution algorithm employed in this study is given as:

1. Current vehicle, \( V \), arrives at the node of interest.
2. Any interference at this node or in the next arc vehicle \( V \) is due? If yes, go to 4.
3. Route (eqns (1) and (2) or (1) and (3)) are used in estimating arrival times at the succeeding node) vehicle through the node into next arc. Go to 17.
4. Is it a major conflict? If yes, go to 7.
5. Hold the other vehicle for \( \Delta t \) units of time to permit the routing of the current vehicle through the node into the next arc in its path.
6. Route current vehicle through node to its next arc. Go to 17.
7. Based on the present vehicle(s) in the conflicting arc, determine the earliest time, \( t \), the arc will be free to receive the current vehicle.
8. Set \( t' = t + \Delta t \), where \( \Delta t \) is the length of time required to route a vehicle through a node.
9. Does the current vehicle arrive at the node from buffer? If yes, go to 15.
10. Is there any other vehicle currently in the buffer? If yes, go to 12.
11. Buffer the current vehicle and schedule it to depart the buffer (i.e. arrive again at the same node) at time \( t' \). Go to 17.
12. Determine the scheduled departure time, \( \bar{t} \), of the last vehicle currently in the buffer.
13. Set \( t^* = \max (\bar{t} + \Delta t, t') \).
14. Place the current vehicle in the last queue position in the buffer and schedule it to depart the buffer at time \( t^* \). Go to 17.
15. Place vehicle in the buffer in the first queue position and schedule it to depart the buffer at time \( t' \).
16. If there are other vehicles in the buffer behind the buffered vehicle in 15, adjust their scheduled departure times from the buffer (if necessary) so that the same ordering of departure sequence is maintained.
17. Exit from the conflict resolution algorithm.
Roboter zurückzuführen. Die Auswirkung der Fehler kann durch die Toleranzen der Werkstücke selbst und die der Vorrichtungen, die zum Auf- und Einspannen dienen, abgeschwächt oder verstärkt werden. In dieser Abhandlung wird ein Modell zur Charakterisierung der Positionierfehler von Roboter entwickelt. Es wird eine statistische Analyse der Positionierfehlerdaten ausgeführt, um daraus Schlüsse auf die stochasticische Beschaffenheit des Robotersystems zu ziehen. Das Grundproblem ist dabei, ob die Positionierfehler der Roboter zustandsabhängig oder zustandsunveränderlich sind.

References
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