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ALTERNATIVE DUAL MODE NETWORK CONTROL STRATEGIES

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16. Abstract From a literature survey a qualitative evaluation was made of four network control strategies for the fundamental control philosophy of the moving synchronous slot. In the literature concerning automated transportation systems, such as dual mode, a great deal of effort has been expended in discussing the pros and sometimes the cons of a specific control concept without reviewing other control strategies that may be available. This paper summarizes the major advantages and disadvantages associated with four control strategies for the moving synchronous slot. A description of each of these control strategies is provided and conclusions are made showing that the deterministic slot/cycle concept and the quasi-synchronous slot concept with entrance station throughput modulated by historic demand data are the most promising. A further study of these two control strategies concluded that the deterministic slot/cycle concept was somewhat better than the quasi-synchronous approach however the issue of system failure and recovery was of such importance that the inability to satisfactorily solve this problem for deterministic control could lead to the abandonment of the concept.

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An evaluation was performed on four network control strategies for the fundamental control philosophy of the moving synchronous slot for the purpose of selecting the most plausible approaches for further development and highlighting the critical problem areas associated with each of the control strategies. The approach used in performing the study was based upon a literature survey and a qualitative evaluation of the proposed concepts. A preliminary conclusion based on system utilization and technical complexity resulted in selection of two possible approaches: The deterministic slot/cycle concept with reservations made in real time, and the quasi-synchronous slot concept with entrance station throughput modulated by historic demand data. A further trade-off study was made for these two approaches to determine if issues such as system design, system failure, or a passenger convenience could be used to select one concept. The conclusion from the study showed that the deterministic slot/cycle system had more benefits than the quasi-synchronous approach, however, the issue of system failure and recovery was of such importance that the inability to satisfactorily solve this problem for deterministic control could lead to the abandonment of the concept.

SECTION 2. NETWORK CONTROL

2.1 GENERAL

The central controller in a dual mode network is expected to be a system traffic coordinator capable of performing collection, processing and storage of information related to billing, historical usage (demand), and real time control of guideway operations. The operation of real time control is concerned primarily with the following functions:[1]

1. Scheduling use of guideway space to avoid conflicts;

2. Routing a trip via some path as determined by the control algorithm;

3. Monitoring or managing the overall network, i.e., monitoring performance, detection of failures, distribution of control to local wayside controllers, etc.

Within these general areas the scheduling of vehicles through the system to avoid conflicts is the first important requirement to be met by a control system. A survey of available literature 1,2,3,4,5 indicates that the moving cell philosophy provides one vehicle control technique that can be used in moving vehicles along a guideway to perform this function. Another control technique that is available for automatic control is the "car following technique;" however, this concept is not considered in this discussion. With the synchronous cell control philosophy, an automated network is covered by hypothetical contiguous cells moving in a pre-established position time profile as shown in Figure 1. Vehicles entering the network are assigned cells which they are to occupy, until the system control reassigns the vehicles to a different cell or until the vehicle leaves the guideway. Four scheduling approaches are available to implement this moving cell philosophy. They are (1) stochastic scheduling, (2) stochastic scheduling using historic data, (3) historical deterministic scheduling, and (4) real time deterministic scheduling. Each will be explained in more detail below. The most critical flow points in an automated vehicle network are the high-speed merge points, where two streams of vehicles come together to form one stream of vehicles[2]. As shown in Figure 2, the merging problem can be handled, using the moving-cell approach, by assuring that coincident or merging cells are not both occupied when vehicles reach a merge point. The merging situation at interchanges in an automated network (as opposed to the simple merge of two one-way streams) will lead to even greater restrictions.[2] Such interchanges could have eight diverge points and eight merge points. Interchange merging is greatly complicated by the fact that a vehicle entering from one direction can leave the interchange in any of three directions.

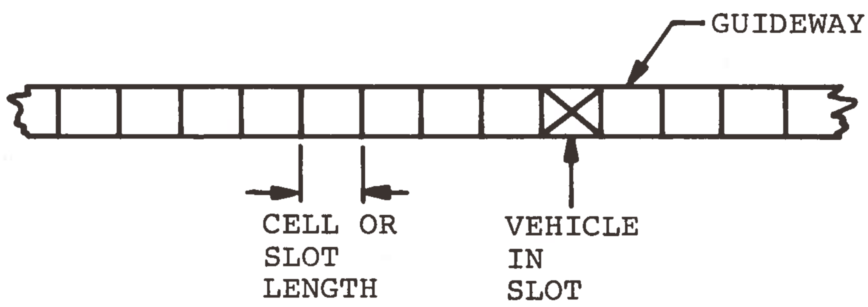

Figure 1. Guideway/Slot

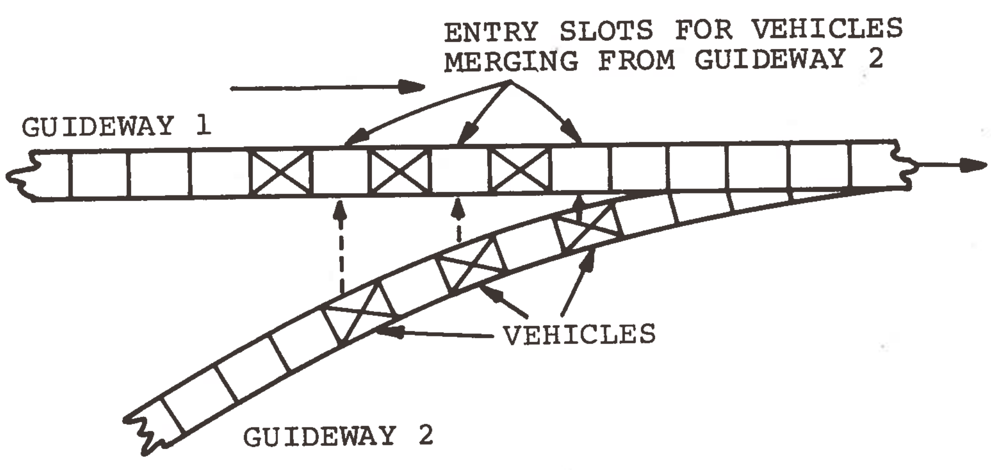

Figure 2. Guideway Merge

2.2 STOCHASTIC SCHEDULING

Pure stochastic scheduling implies that vehicles are allowed on the network based on a space available basis at the entrance terminal merge point. If vehicles are allowed to enter cells on the automated network without consideration of the resultant flows at downstream merge points, as in the pure stochastic approach, a large amount of maneuvering of vehicles between cells in order to provide smooth flow through these merge points is necessary. The maneuverability of vehicles before merges is limited, however, by the distances over which maneuvering can be accomplished and by the performance capability of the vehicle doing the maneuvering.[2] Furthermore, a large number of vehicles impinging on the same merge point can result in large clusters of vehicles at these merges all requiring maneuvering to avoid collisions; hence, allowing unrestricted cell assignment at entrances could lead to situations which will require that vehicles be ejected from the network of queued on the network in order to prevent a collision at a merge point.[3] This chaotic situation is not much better than the present highway system where flows to the network are stochastic.

2.3 HISTORIC STOCHASTIC SCHEDULING

To best utilize a stochastic scheme, scheduling of trips should be determined to minimize unresolved conflicts at the merges. The information required to implement a stochastic scheduling technique to minimize problems, must be collected from real time trip data. This data would be used to apportion certain flows at specific times from each entrance, i.e., a "trip budget" would be allocated each entrance terminal. Historically this budget would be changed as the demand changed in time, (e.g., time of day, day of week, seasonal, etc.). For example, consider the simple network shown in Figure 3. A vehicle located at Terminal A wishes access to the system for travel to some destination designated F. In the stochastic scheduling system the central controller or station controller at A must simply ascertain if an open slot is available upstream at a time such that a vehicle can safely merge into the stream of traffic. At the time of merge the vehicle from terminal A knows nothing about conditions downstream and hence, depending on the flows at merges C and E, a queuing situation could develop either on the main line or from lines C and E. From historic demand data, however, flow from each of the stations could be restricted to some maximum at a given time to reduce the probability of overloading links on a network beyond their capability, and thereby reducing the probability of a queue. In this control process, each vehicle must be capable of slipping slots or advancing slots at intersections to allow safe merges, however, the queue time or length of queue can only be controlled to the degree that historic data can be used to limit flows from stations.

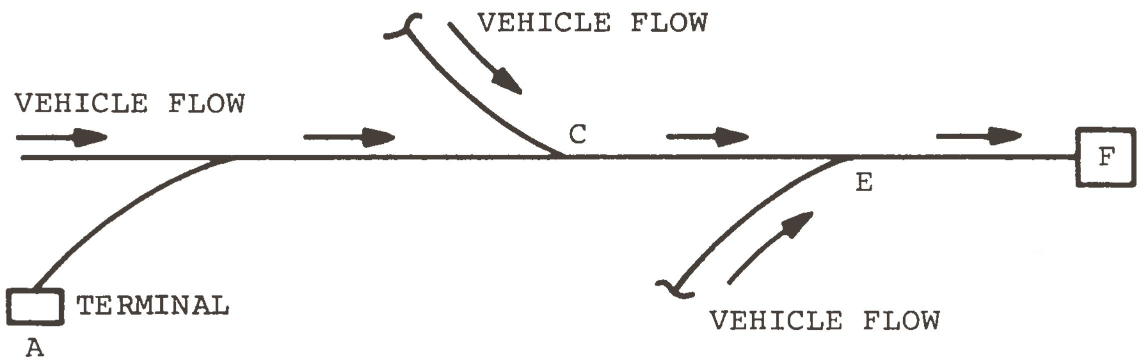

Figure 3. Line Haul Portion of Network

2.4 DETERMINISTIC SCHEDULING - HISTORIC AND REAL TIME

One method to prevent queuing on the network and eliminate possible chaotic consequences, is to assure every vehicle a smooth passage through all of the merges on its route before it enters the automated network. This approach is similar to the guaranteed reservation system utilized in present rail and air transportation systems. This network operating philosophy which routes the vehicle through the network such that all maneuver constraints are met before allowing a vehicle to enter the network, is referred to as preprogramming or deterministic space allocation slot reservation.[2,4,5] The task of assuring smooth passage for all vehicles through a DMV network containing many high-speed merges while maintaining high usage of links and preventing large queues of vehicles at entrances to the network is a difficult one. A DM vehicle on a typical network might, on the average, have to pass through three or more interchanges (or six or more merges) on a typical trip.[2] The importance and complexity of preprogramming becomes even more evident when it is realized that a typical 200 mile network might have 25 interchanges (equivalent to 200 merges) that have to be coordinated under stochastic vehicle demands.

One type of control system preprogramming assigns or pretags slots at entry points for a valid destination. The vehicle travels to its destination without maneuvering at any merge to avoid a conflict with any other vehicle on the network. Computation of the slot-trip scheduling would be performed ahead of time, off line, based on a traffic demand model which could be updated from historic data. Hence, a vehicle requesting a particular trip would wait until his slot came along. A second approach to this basic theme would require the control scheduling system to search in real time for a slot which has not been reserved by any other vehicle. Thus, the scheduler must have information about all trips in progress. The implications of this single-cell or slot programming concept is discussed with respect to Figure 4. Suppose that a vehicle waiting at entrance point A wishes to travel through interchanges 1 and 2 to exit point E. Further, suppose that travel times from B to C, G to C, and F to C are equal, and that travel times from B to D, H to D, and J to D are also equal. If the vehicle at point A upon entering the network occupies the cell which is now at point B, then that vehicle can enter the network only if:

1. The cell now at B is unoccupied;

2. The cells now at G and F do not contain a vehicle which will pass through point C;

3. The cells now at J and H do not contain a vehicle which will pass through point D.

Since all three of these conditions must be simultaneously satisfied before the vehicle at A can enter the network, even moderate flows on the guideway links can result in a long wait for that vehicle at the entrance. The result is a degradation in entrance station efficiency and guideway utilization.[3]

In a larger network than that shown in Figure 4, moderate flows on network links would result in long waiting times at many entrances to the network. The end result is that large queues of vehicles build up at entrances while at the same time link volumes are low. Since these effects are contrary to a goal of maximum link utilization for a DMV system, other types of preprogramming should be considered for complex networks.

A variation of this basic slot prescheduling technique requires vehicles to shift from one cell to another cell, i.e., to maneuver, in order to negotiate a merge. One such possibility for preprogramming requires that the exact cell that a vehicle will be in just after each merge point on its route be preplanned before a vehicle enters the network. The vehicle or the central computer would store this information and the required maneuvers would be performed at the appropriate times. This type of preprogramming requires a tremendous storage of information about the relationships between the positions of all vehicles on the network. The maneuvering plans of many vehicles already on the network would have to be considered, and perhaps modified, by the central computer before a decision could be made about allowing a single vehicle to enter the network. This method is similar in concept to the historic stochastic scheduling process except that all conflicts are resolved in real time by a control computer prior to processing a vehicle from a station to the network, rather than resolving conflicts at merges via local

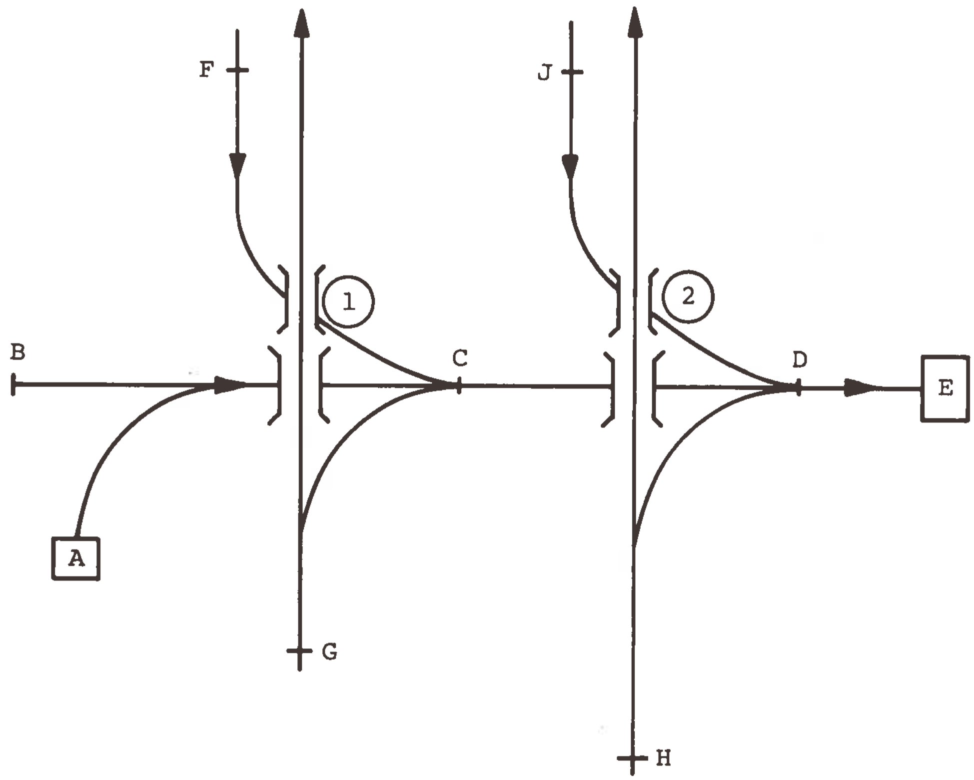

Figure 4. Network Intersection

controllers and allocating "serving budgets" to stations based on historic data. The central computer data processing requirements would be large for this system.

2.5 SLOT/CYCLE DETERMINISTIC PRESCHEDULING

A type of prescheduling which uses some of the attributes of stochastic maneuvering at merges and guaranteed free flow through the system is the slot/cycle concept. Maneuvering of vehicles is required, but the exact cell that a vehicle will occupy at each merge point is not preplanned before the vehicle enters the network. Instead, only the availability of an empty cell among a group of cells is preplanned. Hence, information storage requirements are greatly reduced, and the central computer does not need to consider the specific future actions of many vehicles before allowing a vehicle to enter the network.

The strategy for this type of preprogramming, which will be called cycle/slot preprogramming, is as follows:[2]

1. Define a cycle as a group of (n) contiguous slots (typically $n < 10$). The exact time that a cycle at an entrance will begin to pass through each downstream merge point of the network is known.

2. A vehicle enters a specific cycle at an entrance and is never allowed to move out of that cycle while in the network.

3. A computer keeps track of the number of vehicles already on the network which will be present in all future cycles at each merge point. (The number of cycles that the computer must keep track of, at a specific merge point, depends on the distance from that merge point to the upstream entrance that is farthest from the merge point).

4. Since a cycle has (n) slots, (n) is the maximum number of vehicles which can be scheduled to pass any merge point in any given cycle.

5. A vehicle at an entrance is allowed to enter the network in a given cycle only if, at each merge point on its route, less than (n) vehicles are already scheduled to pass that merge point in the considered cycle. Obviously, there must also be less than (n) vehicles in the cycle that the vehicle will occupy when it first reaches the guideway, and the entering vehicle must be assigned to an unoccupied slot in that cycle.

6. Vehicles maneuver under local control, on the ramps in the interchange area, in order to assure that each slot in a cycle is assigned no more than one vehicle at the merge points in the interchange area. Because any maneuvering of vehicles on an inbound lane must be accomplished among vehicles that will have different output directions, and since the flows on all outbound lanes of an interchange must be considered simultaneously, very little useful maneuvering can be accomplished before reaching an interchange.[3] More efficient maneuvering can be accomplished on the ramps withing the interchange area when the vehicles are segregated with respect to output direction.[3]

7. The number (n) of slots per cycle must be chosen such that local maneuvering can always accomplish merging at all interchange areas in the network.

This concept results in allocating all queueing to the stations, complete information to the user on probable wait and travel time prior to entering the system and a guaranteed non-stop journey once on the network, assuming no failures. The control and scheduling system requirements are complex at best and a thorough analysis of throughput for extensive networks with many merges has yet to be evaluated. Preliminary investigation[3] has determined that vehicle ability to enter the network improves as the number of slots per cycle increase to some level, e.g., less than 20, but the number of slots per cycle is limited by the space available for maneuvering on interchange ramps and a time synchronization problem between cycles merging at intersections. The interactive nature of these constraints is reviewed in Reference 6.

SECTION 3. COMPARATIVE ANALYSIS

The choice between the above alternatives is a function of technical feasibility and the goals established for the dual mode system. With respect to the latter, a need for maximizing vehicle throughput is postulated as the most likely goal, i.e., maximize the number of vehicles passing any given point on a guideway at any given time.

3.1 SUMMARY - ADVANTAGES AND DISADVANTAGES

With respect to the above criteria the following comments are made relative to each of the control concepts:

1. Historic Deterministic Prescheduling - Slot Concept

   Technically a simple scheme, however, since it is relatively inflexible because of the nature of user demand, utilization of the system will be less than than with some of the other concepts.

2. Real Time Stochastic Scheduling

   From a command and control viewpoint the major scheduling emphasis is placed on the local controller. Vehicles are assigned on a space available basis at the local merge, thereby maximizing the number of vehicles on the system. However, the on line guideway queuing problem could decrease throughput. Technically it is relatively simple, however, utilization in terms of throughput could be small.

3. Historic Stochastic Scheduling

   This has the inherent advantage of processing vehicles on a simple space available basis coupled with a historic data base budget to allocate some specified maximum flow rate from each terminal to minimize the probability of conflicting merges resulting in large queues.

4. Real Time Deterministic Prescheduling - Slot Concept

   Searching for a non-conflict path through a major network on a single slot basis would result in a low overall throughput plus it would require the control computer to store information on the exact location of each vehicle in the system. Therefore, technically it is complicated and its throughput will be low. Allowing maneuvering of vehicles in the system to increase throughput would place an enormous burden on the central computer.

5. Real Time Deterministic Prescheduling -Slot/Cycle Concept

The cycle concept with (n) slots/cycle and with vehicle maneuvering capability within cycles increases the probability of finding a "non conflicting path" through a network. It reduces on-line queues to zero, and has increased throughput compared to the single slot concept. The network control and scheduling system is probably more sophisticated than any of the other systems since real time interaction processing of large amounts of stored information is required between all portions of the system.

3.2 PRELIMINARY CONCLUSIONS

Based on this preliminary study as summarized in Table 1., it appears that the most probable system for automated control is either the historic stochastic scheduling approach or the real time deterministic prescheduling system utilizing cycles. In order to gain some insight into each of these systems, it is necessary to examine each of these concepts in more depth relative to impacts each may have on a total system

TABLE 1. CONTROL SYSTEM SUMMARY

	ADVANTAGES	DISADVANTAGES
1. Real Time Stochastic Scheduling	Technically simple-Schedules vehicle to network on space available at entrance ramp	Problem of large queueing on system would lower throughput
2. Historic Stochastic Scheduling	Technically within state-of-the-art minimizes queueing on system utilizing historic demand data	Poor demand prediction model would result in queueing on system
3. Deterministic Scheduling-Historic (Slots)	Technically simple-Preassign slot to destination	Random arrival of vehicles at stations would result in lower utilization than other concepts
4. Real Time Deterministic Prescheduling (Slot)	None	Searching for non-conflict path through a large computer storage required to keep track of all vehicles
5. Real Time Deterministic Prescheduling (Slot/Cycle)	Smooth flow of vehicles on network. No queueing on network. High utilization	Network control system and scheduling system more complex

The major functional difference between the two, in terms of traffic flow on the system, is the method by which successful merging is accomplished at intersections. Using the stochastic system with synchronous control, each merge point to be negotiated in the system could cause a queuing problem, with vehicles being rejected from the system or being routed on an alternate path, if available. Additional lengths of guideway and dissatisfied customers are potential major drawbacks. With the deterministic system all paths are prenegotiated, and again, assuming proper system synchronization, no queues occur. Computational requirements, however, for the central computer can be very large. For the stochastic system, each ramp, once designed, can handle a finite number of stopped or nearly stopped vehicles before the queue length causes a slowdown or stoppage of the feeding lane. As the historic demand data base, which can be used to meter vehicles from terminals into the main stream, becomes refined these queue lengths can probably be maintained at some reasonable length. If the design incorporates real time information about the merge situation at critical intersections, the station budget allowance can be refined further. Using this demand information, flow rates from upstream terminals can be limited to maintain flows such that successful merging can take place with minimum guideway queues while attempting to maximize the number of vehicles flowing on the system at a given time. In the ultimate, the demand predictions could become accurate enough to disperse vehicles from terminals at rates which allow successful merging with zero or nearly zero queue time.

The deterministic slot/cycle process on the other hand achieves this end immediately. It effectively manipulates terminal demand data in real time and allocates, in a predetermined manner, routing through merges to a destination. Hence, the conclusion is that since a stochastic process approaches the deterministic process in the limit, i.e., the stochastic system can approach but not exceed the throughput achieved by the deterministic system.

SECTION 4. STOCHASTIC VS. DETERMINISTIC SCHEDULING - ADDITIONAL ISSUES

In addition to the utilization or user service level issue associated with selecting the best control strategy, other factors need be considered. Such issues are concerned with network performance, system design, and user comfort and convenience; these are discussed below with respect to the modified quasi-synchronous historic demand and the deterministic slot/cycle control strategies.

4.1 NETWORK PERFORMANCE ANALYSIS

4.1.1 Network Capacity

As discussed above, the deterministic system should achieve the best utilization for a given network design.

4.1.2 Network Synchronization

The definition of synchronization is best explained with the aid of Figure 5.[2] For the deterministic system suppose a cycle begins to pass point K at time t = 0. If the segment of guideway KL is to operate synchronously, then the times t_K that a cycle begins to pass point K must satisfy

$$t_K = iT; \quad i = 0, 1, 2, \ldots \qquad (1)$$

where T is defined as the time it takes for passage of one cycle, i.e., T = one cycle time. There are two paths from A to K, namely, path ABCK and a longer path AEFGHK, of lengths d_{ABCK} and d_{AEFGHK} respectively. In order for (1) to hold, the travel times along these paths must satisfy the relationship $t_{AEFGHK}-t_{ABCK}=i_1 T$, where i_1 can be any integer. Secondly, the control computer keeps track of all reservations on the system and all vehicles in any given cycle must maintain operation in their preassigned cycle. Time synchronization is then defined as superimposing complete cycles from each merge line. Vehicle synchroniztion is simple assuming that vehicles in a given cycle always remain somewhere in the preassigned cycle. Local controllers handle the actual maneuvering and merging of vehicles in a cycle at intersections; however, the reservation strategy dictates that the central controller identify the number of vehicles in any given cycle. Any deviation from cycle synchronization on any link would represent a malfunction. Similarly any vehicle slipping from a cycle would represent a malfunction.

For stochastic operation, synchronization of slots is still required. However, since the local controller does the merging on a simple space available basis as vehicles arrive, each vehicle must maintain its assigned slot only during the merging process.

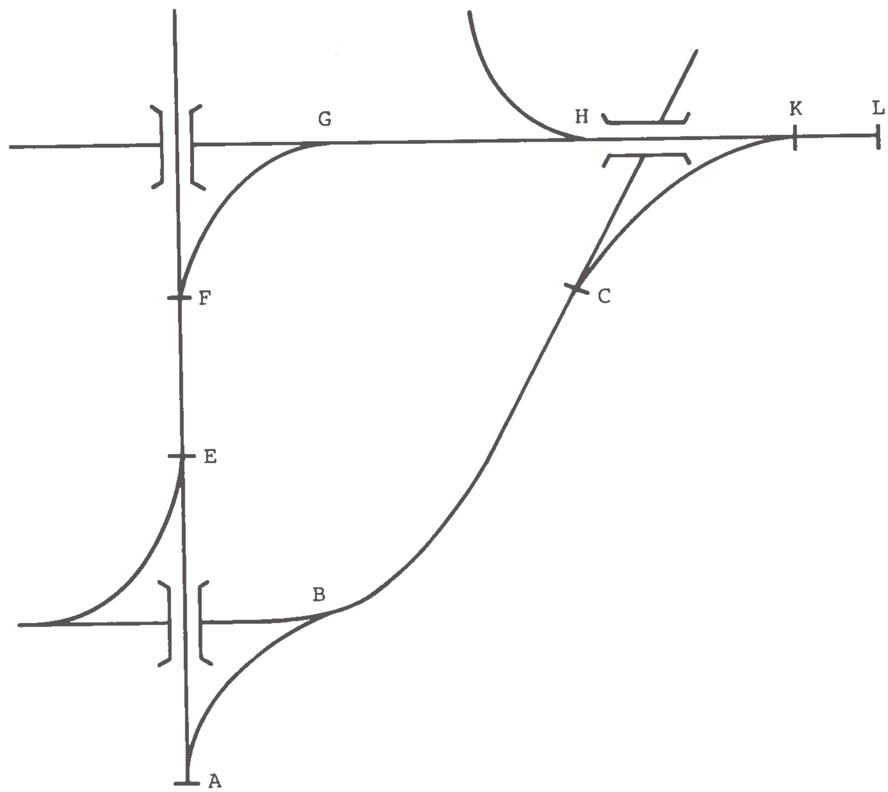

Figure 5. Portion of Network

During normal line operation, a vehicle could deviate from its assigned slot and as long as the central computer was updated frequently relative to this operation, network synchronization and hence remaining system operation would not be effected.

4.1.3 Vehicle Performance

On the surface it would appear that the deterministic control strategy would impose greater requirements on vehicle performance due to the requirement of maintaining a preassigned cycle, for the duration of the trip. However, since the critical maneuvers of acceleration and braking are determined by a position time profile maintained by the local controller in either system, the vehicle's normal operational performance requirements will be the same. For the deterministic system, however, there must be more assurance that a vehicle can maintain its assigned cycle for the duration of the trip, since by definition, any vehicle slipping out of its assigned cycle represents a failure. Also, the performance of the worst vehicle will dictate the design of the system in terms of maneuvering capability and speed.

4.1.4 Network Failure

In the deterministic system, failure of cycle synchronization, local failure of a section of network or a vehicle malfunction will effect the total operating network. At the present time there is little information available on system recovery (start-up) from a failure associated with the deterministic control strategy. In the stochastic system since the merging condition is not precalculated and the local controller provides this merging function on an arrival basis, a single vehicle or link failure will only impact those portions of the network feeding the area in which a malfunction occurred. Recovery from a failed condition again should be easier than with the deterministic control strategy.

In general, what is desired to recover from a failed condition is the ability to re-route or by-pass that portion of the network which has been affected.

Assuming that some means is available by the central and wayside computers to detect and isolate a failure then a by-pass or emergency lane fabricated as a "third lane" at the time of system implementation could solve the physical problem of moving vehicles.[2] Suppose that in Figure 6 guideway lanes 1 and 3 carry traffic in opposite directions, while lane 2 is a bi-directional lane used only if a breakdown occurs in lane 1 or lane 3. Further, suppose that a breakdown has occurred at point A and that vehicles on lane 3 are to be diverted to lane 2 at B and are to return to lane 3 at C. For the deterministic control strategy in order for the system to remain operating time-synchronously, and such that vehicles arrive at their proper cycles at downstream merges, the control system must assure that the travel time along the alternate path BEFC is the same as the usual travel time along the path BAC, in spite of the fact that the distances from B to C along the two paths are not equal. Obviously, the overall control system must have the capability to effectively cause vehicles using an alternate path to travel at an average speed which is dependent both on the length of that alternate path and on the travel time on the usual path. For the stochastic system, synchronous time operation for slots is required only at merging; however, since merging is handled via the local controller, the different path lengths would not require that vehicles traveling a longer path move at a higher average speed to maintain the same travel time. Due to the fact that system failure and recovery has had relatively little emphasis, this area needs additional analysis prior to really being able to select one type control strategy. Specifically, the issues to be analyzed are directed at the type and frequency of failure and the options available for quick recovery from these failures.

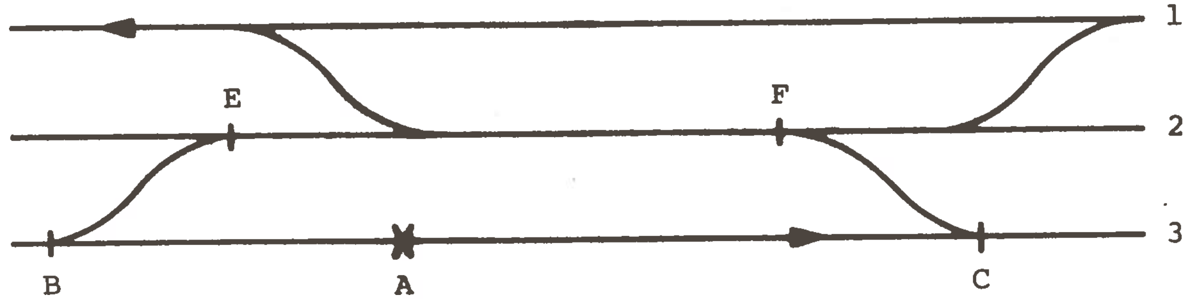

Figure 6. "Third" Lane for Emergency Use

4.2 SYSTEM DESIGN

4.2.1 Interchange Merge and Ramp Design

A typical design for a dual mode intersection is shown in Figure 7. Vehicles travel along the two guideways from preceding intersections or stations with the understanding that merging must occur at the designated merge points. Under synchronous deterministic control the vehicle route is predetermined through the central computer. It has been shown that maneuvering of vehicles prior to a switch point is not an efficient method of rearranging vehicles.[2] Vehicle maneuvering in a cycle is handled by the local controller. The interchange ramps following the switch become the maneuvering region for all vehicles. The length of this merge ramp is dependent on the performance capability of the vehicles, the number of slots/cycle and a requirement of cycle synchronization at the merge. In a stochastic system operating under quasi-synchronous control the local computer considers the destination of vehicles at switch points as well as commanding the maneuvering requirements. If the decision is made to perform all maneuvers on ramps (as in the synchronous deterministic concept), then each merge ramp must be designed to handle a finite queue length. An abort lane to the local street network must also be provided. If the decision and maneuvering region is placed on the guideway prior to the switch point, it is possible to solve unresolved conflicts at merges by routing vehicles along alternate paths. In Figure 7, for example, vehicles which might normally want to switch from point C to D would go to B if an unresolved conflict situation arose. Since the merging process is not predetermined by the central control unit and vehicles-slot synchronization is performed at the local controller level, the interchange design requirements on ramp maneuvering length and cycle time synchronization are not as demanding. However, additional link sections of

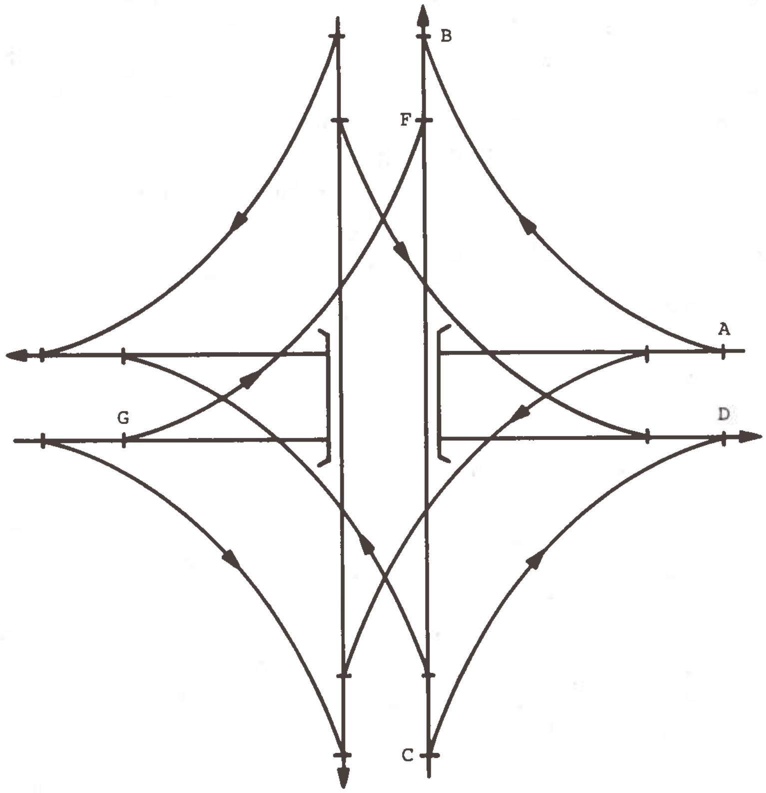

Figure 7. Four Way Intersection

guideway are required, to route vehicles along an alternate path.

4.2.2 Entrance Terminal Design - Processing Stations

The problem of adequate terminal design in terms of size (no. of processing stations) and configuration (series, parallel, or series parallel processing) is a function of the generated demand and the overall waiting time of a vehicle prior to entering the network. Under the pure stochastic philosophy (quasi-synchronous, non-reservation) vehicles are simply dispatched as a function of available space at the local merge and the existing serve rate (processing, scheduling and inspection time) of the terminal. Therefore the queuing area requirements at the station are a function of these variables. With the stochastic scheduling strategy, demand modified, or the deterministic synchronous strategy, an additional portion of the terminal must include a temporary vehicle storage area to hold vehicles waiting for the appropriate slot or cycle. This additional storage area will be a function of the demand of that station coupled with the demand created on the network by stations feeding critical merge points. In the historic stochastic control case the number of processing stations in parallel is simply a function of the server rate of each processing station and the desired flow rate from that terminal to the network. With deterministic scheduling since the user schedules his desired destination, the station design to be efficient must accommodate situations where vehicles scheduled for shorter trips (i.e., scheduling through no merge points) can be processed faster than vehicles who may have to wait longer before getting clearance through many conflicting merges. This can be handled by adding parallel processing stations (probably expensive) or by providing bypass lanes around a general queuing area. Consequently optimal station design is dependent upon selected control strategy. The control strategy desired would maximize guideway utilization and should also minimize the queuing area requirements for a terminal for a given demand.

4.2.3 Exit Station Design

The design of exit stations or exit ramps is similar to the problem encountered in designing merge ramps with respect to the control system. With deterministic control the guaranteed no conflict path could include scheduling to the existing street network based upon a pre-established value of the throughput that the local street can accept. Hence, with a given exit station design the demand for that exit can be controlled prior to entering the system to prevent queuing at the exit. This is an important aspect of the deterministic approach. With the non-reservation quasi-synchronous approach, modified with historic demand, the exit queuing problem can be controlled only to the extent of how well historic prediction can control the flow in the system. Hence, exit designs with the latter control strategy should include some queuing area to accommodate unpredictable fluctuations in demand.

4.2.4 Command and Control Requirements - Central Control, Wayside Control and Vehicle Equipment

Very little has been done in the way of sizing and costing of control equipment for large scale (200 mile) networks operating under automatic control regardless of the control philosophy. For the two control philosophies recommended for further consideration, some overall functional requirements are apparent; however, whether hardware is available, or can be made available and be cost/effective, has not been established.

Central Control The basic functions required by the central control unit relative to network control with the deterministic slot/cycle concept are:

1. Processing reservations from all processing stations and allocating a route structure based on some algorithm (minimum time for example);

2. Keeping track, in units of time, the position of each cycle in the network and the number of vehicles in each cycle;

3. Communicating with trackside detecting equipment to insure that the assigned vehicles remain within given cycles, also, monitoring the local wayside command systems to insure that merges or demerges have occurred;

4. Maintaining synchronization of the network;

5. Providing some means of isolating failed portions of the network and instituting some recovery procedure.

The non-reservation quasi-synchronous concept imposes the following basic functions on the central computer:

1. Maintaining a historic demand data base and apportioning throughput requirements on each input terminal;

2. Communicating with trackside detecting equipment and the wayside control system to monitor the position time profile of all vehicles in the system to detect failures;

3. Provide a means of detecting and isolating failed portions of the network.

Wayside Control The wayside equipment for each of the control strategies provides the control necessary for merging and demerging. In the deterministic system this equipment is also required to provide differing commands to vehicles located in the same cycle. For the stochastic system the controller must be capable of detecting queues at intersections and provide a communication base capable of resolving queues before the queuing situation can significantly effect the utilization of the network.

Vehicle Control Equipment With respect to the communication and information storage requirements of vehicle associated equipment, some hardware trade-off exists between the wayside controller and the vehicle. For example, switching commands can be stored in the vehicle or commands to switch can be generated from the wayside controller. For the deterministic system, since merge conflicts are eliminated by the central controller, vehicle control equipment need not communicate with the wayside controller the intention of a vehicle to switch or not switch. With the quasi-synchronous non-reservation philosophy, since the routing is not pre-established in a central computer, a vehicle storing its own switch commands must communicate this information to the wayside unit in order to avoid major queuing problems.

4.3 USER CONVENIENCE - WAITING TIME AND SERVICE TIME

With respect to passenger convenience, measured in terms of service and waiting times, each control system strategy has a different impact. In the deterministic synchronous system, a passenger upon placing his reservation, can be told what his exact trip time will be when on the system, and the amount of time he must wait before his trip is initiated. He can then be given an option as to whether he wishes to continue his trip on the dual mode network or choose an alternative mode. It is also conceivable that an automatic display board could be placed prior to entering a station displaying typical wait, and travel times to a few (3-4) of the more common or critical destination points. With stochastic scheduling, historic demand data can be used as an information base to provide the same information, however, the reliability of the data would only be as good as the projection derived from the historic data. Also since queuing and/or rejection from the network is possible on the system, some portion of trip could result in waiting on the network or being completed off the network.

With stochastic control, vehicles can be serviced at entrances on a first come first served basis since final destinations are not considered in the routing process. With deterministic scheduling, shorter routes, i.e., vehicles traveling through a minimum number of merges at an intersection, could be serviced easier and faster thereby allocating priority to the short route traveler. While this has some advantages in terms of utilization, it could be detrimental if some overall management scheme is not instituted to balance trip length and overall waiting time.

4.4 FINAL CONCLUSIONS

The major issues associated with the two leading control strategies have been qualitatively evaluated. A summary of the important impacts, issues and problem areas are highlighted in Table 2. As seen in the table and discussed in the text, both control strategies are deficient with respect to fully defining the size, function and interface definition of the central, wayside and vehicle command and control equipment.

The deterministic system while providing some pluses in the areas of utilization, interchange design and passenger wait time, needs investigation in the area of system failure and recovery. The non-reservation system is weakest in the area of merging control and intersection design. Hence, while a positive conclusion on control strategy cannot be made to date, the deterministic system appears to offer more benefits if the system failure and recovery issue can be solved.

TABLE 2. CONTROL STRATEGY COMPARISON SUMMARY

	Quasi Synchronous Slot Non-Reservation Control (Historic Demand Modified)	Synchronous Slot/Cycle Deterministic Control
Network Capacity	Approaches Det. strategy. Limited in terms of historic demand data & feedback loop delays from critical intersections	Should have highest utilization measured in terms of vehicle throughput
Network Synchronization	Synch of slots not mandatory except during merging process. (Vehicles allowed to slip without limit except at merge)	An absolute must for entire system (vehicles must occupy given cycles)
Network Failure	Should be capable of link shut down & start up without "serious problems" due to lack of synch. requirements	Could be detrimental to system - no known convenient way to shut down & start up failed link because of synch. requirements
Vehicle Perf.	Vehicle can "slip slot" except during merge	Must maintain cycle always. Slowest vehicle in terms of maneuvering, input to cycle size selection
Inter. & Ramp Maneuv. Design	Ramp length function of speed must allocate space for "some" queueing or provide abort lane	Ramp length (MIN) function of cycle size, speed & vehicle maneuverability no queuing space required
Entrance Station Design	Function of input demand, throughput restrictions and processing time. First come first served	Function of input demand output distinction of vehicle & processing time. Design can accommodate serving vehicles on basis of destination rather than first come first served
Exit Station Design	Station should allow "some" queueing area to accommodate unpredictable stochastic arrival of vehicles	Exit station throughput can be accommodated with reservation scheme
Computer & Control Reg.	Central Control System must aportion trip budgets to terminals to minimize queue problem at merges	Central control system must have ability to process reservation requests from terminals in real time, keep track of cycle occupancy and maintain system synch.
Passenger Convenience	Passenger waiting time could be "split" between entrance station, guideway, exit station. Prior knowledge of "exact" trip time not known	All passenger waiting time done at entrance station - once reservation requested, trip & waiting time are known.

SECTION 5. RECOMMENDATIONS

While a definite conclusion could not be reached in terms of selecting the best or optimum control strategy for a dual mode application, the analysis process did focus on areas in which additional work is required. Some of this work is being performed in various areas as indicated in References 3 through 8; however, additional analytical studies are required which consider the full scope of all the major system elements.

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