simulation modeling. However, much of the previous research and performance prediction was at significantly higher demand densities than have been observed at Haddonfield or most other demand-responsive systems. The implication of these lower demand densities is that the economies of scale possible with these systems cannot yet be realized—and that productivities of 5 to 8 passenger trips per vehicle hour are more realistic than previously cited ranges of 9 to 13. Stress must now be on making the service more attractive to potential users so that economies of scale can be achieved and at the same time increasing productivity for a given quality of service. With regard to integrating DRT and fixed-route transit, the computer must be used to make the overall service more attractive and to enable larger systems to be operated. Current research at M.I.T., which is addressing all these issues, strongly suggests that it is both feasible and desirable for the computer algorithms to achieve better service and to allow the operation of large integrated DRT and conventional transit systems.

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Few people deny that one of the major problems today is the satisfaction of demand for an attractive, practical, economic alternative to the door-to-door transportation service offered by the automobile. Although much public and private money has been spent on the conveyance aspect of transportation, this expenditure has not brought us much closer to the development of an alternative to the automobile.

Many people think that the personalized transportation service offered by demand-responsive transportation technology provides this alternative to the automobile. If this is so, why has this new technology not been adopted by professional transit people to any great extent? The fact remains that most current DRT systems have serious defects for the practical transit operator.

DEFECTS IN DRT TECHNOLOGY

What are some of these defects? We suggest that too little attention has been paid to the economic efficiency of vehicle use in DRT applications. The current pressure to maintain high DRT service levels and the labor-intensive cost structure have reduced vehicle economic efficiency to such an extent that no conventional transit operating budget can long sustain such a DRT system.

The second defect in current DRT technology is its inability to provide practical DRT services to a large geographic area where, for example, door-to-door travel times could be as long as 2 hours. Another aspect of this defect is the current lack of DRT technology to truly integrate with express bus or rail transit facilities in a large area.

The third weakness in DRT technology is the poor accuracy of current scheduling methods. Given fixed resources, promised response times grow less and less reliable as demand increases. This fault is not so much due to the inability of current scheduling methods to cope with DRT demands as to the lack of scheduling tools that can assist in carrying out the methods while keeping up with the demands. Therefore, the scheduling of increasing numbers of vehicles or passengers or both, plus the introduction of other complexities such as the integration of DRT and other forms of transit, is hard to imagine without some automated scheduling assistance.

AUTOMATED SCHEDULING ASSISTANCE

To assist the scheduling (and dispatching) functions of DRT control and to help overcome the defects, LEX has developed various levels of automated control system technology for the newest DRT designs. This technology is based on a minicomputer, which has proved to be a relatively low-cost, highly reliable, and tireless DRT scheduling "assistant." Depending on control needs, such a service area size and population density, one or more of these minicomputers can be used to control (i.e., schedule and dispatch) 6 to 75 vehicles each. Furthermore, when more than one computer is required because of system size, they can be interconnected to provide mutual backup in case one machine fails.

Of course, there is nothing new in using a computer to schedule vehicles. So what is new? Basically, what we have done is add the dimension of adaptive control to the computer programming. To put it more simply, we have programmed the computer to tell the transit operator how the system is doing and how to make it perform better.

Adaptive control systems vary in sophistication from the household thermostat to complex control systems that process chemicals automatically in huge plants. Whether control systems measure one operation or several operations such as temperature, viscosity, and volume, they have in common the fact that all points of measurement are manually set or programmed. Standard control systems, in other words, check the process functions against an absolute standard like the temperature setting on a furnace thermostat.

Although the setting on a thermostat is a standard control point system, we can change this absolute control point at will. The thermostat gives us the ability to adapt the heating system instantaneously to our changing personal needs. In fact, a thermostat is an adaptive control instrument with which to change the household environment.

LEX has applied this same adaptive control methodology to its latest vehicular control system designs. Our adaptive control methodology is based on a management information system (MIS), which is an automatic feedback by-product of a computer-assisted scheduling and dispatching system. We use the MIS to tell how the transit system is doing and how to change the control points by means of what we call a parametric screen so that the system performs against goals, or control points, that reflect expectations.

The MIS records operational transit statistics. For example, it records quoted pickup and delivery times directly from the reservationist's video input screen. Actual pickup and delivery times are recorded from the dispatcher's screen when he or she receives the transmission from the bus driver that a stop has been completed. Because a clock in the computer documents each transaction, the dispatcher is only required to mark the trip completed on his or her screen by hitting a key on the keyboard. The management information system has now documented quoted times and actual times so that the level of service and deviation from quoted time analyses can be made. All this valuable documentation is done with no additional control-room personnel effort. The information is always complete and accurate, although accuracy of actual times is dependent on the driver's contention for radio time.

Analysis of the MIS reports is the first step in our adaptive control methodology. It is analogous to realizing that 70 F (21 C) temperature is making you too warm. Changing certain control points or parameters is the adaptive part of an adaptive control process. Supervisory personnel can use the parametric screen to easily make corrections. Changing control points is just as easy as inputting normal reservation data into the system. Examples of the control points that might be changed by supervisory personnel are travel time goals, necessary rendezvous times with other transit systems, and estimated travel times between reference points in the system.

The MIS also identifies when and where trips begin and end by each zone or reference point in the service area. Thus, one can identify where the more cost-effective alternatives to DRT services, such as bus pooling or express routes, may be established.

This level of adaptive control methodology is required if a DRT system is to meet the expectations of the public and is to be integrated with other available transit services. In addition to what I have described as an "instantaneous" adaptive process, the management information system maintains the data over time and summarizes them, which allows DRT system management to consider adaptive changes that may only be evident by comparing the data assembled during long periods. Such an example may be the travel patterns of users during times of the month that would indicate how critical resources (vehicles) should be allocated between service centers by days of the week and times of day. Proper allocation of resources will bring certain economies to DRT systems. Management information is systematically accumulated by the computer on the vast Santa Clara County DRT project, currently the largest integrated DRT system in the world, and the system generates sufficient data to enable adaptive optimization of all performance parameters over time. In other words, based on past performance, the system is constantly improved.

A second level of control technology has been programmed into our computer-assisted scheduling and dispatching system. It can best be described as an automated adaptive control process. The system can perceive a problem and immediately reset its own controls to adapt to the situation.

We are now using this adaptive control system to guarantee pickup times and, to a lesser degree, any quoted delivery times. Some understanding of our unique scheduling control program is required to understand the use of this control system. In our computerized system, we preset a scheduling requirement for pickups to be made within 15 minutes. We call this a goal, and we refer to the process as goal-oriented scheduling. A vehicle scheduled by this method may not be the closest to a pickup point, but it will be the vehicle most likely to reach that point in 15 minutes (± 5 minutes, which is what we currently allow in the system). If no vehicle can meet these expectations, then a new time is set for that pickup, if it is acceptable to the customer. Most important, the system has, as its primary objective, reliability of quoted pickup times. If the passenger also has a delivery time constraint, that time becomes part of the computer scheduling "test" and also a part of future tests for future scheduled stops on that vehicle so that the quoted delivery time will not be violated. This automated adaptive control system works for individual stops.

A second application of automated adaptive controls in our scheduling system occurs when heavy demand makes reliance on 15-minute pickup times infeasible. As this situation is identified by the system (as a result of several new-time quotations previously described), the system will alert the supervisor via the supervisor's video screen.

The control supervisor can introduce new buses into the system or, in the case of a multiple service area system like that in Santa Clara County, he or she can reallocate buses from another service area experiencing less current demand.

If, however, resources cannot be increased, the system will set a new control for the pickup time, in this example, perhaps 20 minutes. All control center personnel are notified automatically on their video screens of this change, and the change stays in effect until events require an adaptive control reset to 15 minutes. These are automated adaptive control situations because no one is required to change control points, although it can be done via the parametric screen. The system corrects itself based on historical knowledge and, of course, will reset based upon the preset goals, in the case of Santa Clara County, a 15-minute pickup time.

We believe that the large number of "no-shows", which may be as many as 250 out of 700 trips in some DRT systems, result from vehicles arriving too early. Either the passenger cannot respond because he or she is in some state of unpreparedness or he or she does not expect the vehicle and, therefore, in the case of some elderly users, does not hear it.

We believe provisions for easily changing control points and system parameters and the resulting constant system tuning are fundamental to the development of reliable, fully integrated transit systems. These systems require modern computer technology. Together with computer contributions to the scheduling and dispatching functions, these systems are capable of supporting DRT services that not only serve low-mobility people but that offer the time-sensitive people a reliable alternative to the automobile.

The cost of data capture and reporting alone indicates the economic feasibility of some form of data processing in every DRT system. If improvements in scheduling accuracy are required, at the least, a minimal computer-assisted DRT control system should be used. A truly integrated DRT and express bus system, in which multiple demand-responsive trips are coordinated with the express bus schedules, requires a substantial computerization of the entire operation.

Computerization of a DRT system is not so expensive as previously thought. Current cost data on the operation of manual and computer-assisted DRT systems indicate that manual control systems may not be cost effective if more than 5 or 6 vehicles are operated because computerized control systems are less labor intensive after a minimum number of controllers are employed. Computer-assisted scheduling and dispatching can effectively schedule more passengers per vehicle mile, and that reduces operating costs and ultimately the need for more capital equipment.

The hardware system configuration used in Santa Clara County and our research (although differently configured) are capable of growing without added equipment from a system to control 5 to 15 vehicles to one that controls 50 to 75 vehicles. The cost of the computer, of course, remains the same, and as the system grows hardware cost becomes an increasingly small percentage of the total operating cost. When capacity is reached, hardware costs are only 1 to 5 percent of all costs.

Table 2 gives some typical cost figures generated from our paratransit model and 4 months of actual simulation service in Santa Clara County. Manual system data come from the Haddonfield system (shorn of demonstration costs) and one of the service areas in Santa Clara County that uses manual control.

Given this economic cost structure, manual control systems may not be so economical as computer-assisted systems, particularly when one considers the ease of obtaining accurate and timely performance data captured automatically by the computer. These data and a statistical program can supply much of the adaptive feedback required to ensure that the system will meet its current system goals or to modify those goals if the statistical analysis so indicates.

Because of the advent of microprocessor electronics, the outlook for adaptive DRT computer-controlled systems looks even better than the current economics indicate. Substantial reductions in the cost of digital hardware are forecast by leading electronic market research institutes. These reductions in cost, coupled with the inevitable rising cost of labor, tilt the scale even farther toward the advent of fully computerized DRT control systems, regardless of their size. Current advanced research in applying microprocessor electronics promises to reduce the cost per vehicle of computerized scheduling, including digital vehicle instruction displays, to a level below the cost of, for example, the air-conditioning apparatus in the current DRT vehicles.

Table 2. Costs of manual and computer-assisted scheduling and dispatching.

Type	Number of Vehicles	Number of Controllers Per Shift	Control Labor Cost[a]	Control Equipment Cost[b]	Real Control Cost	Scheduling Effectiveness Factor[c]	Effective Vehicles	Imputed Control Cost[d]	Effective Control Cost[e]	Effective Control Cost Per Vehicle
Manual	5	2	64	–	64	0.85	4.25	45	106	21.8
	10	4	128	–	128	0.75	7.5	150	278	27.8
	15	6	192	–	192	0.50	7.5	450	642	42.8
Computer-assisted	5	2	64	32	96	0.90	4.5	30	126	25.2
	10	3	96	32	128	1.00	10	0	128	12.8
	15	4	128	32	160	1.00	15	0	160	10.7
	15	4	128	48	176	1.00	15		176	11.7
	20	5	160	48	208	1.00	20		208	10.4
	25	6	192	48	240	1.00	25		240	9.6
	30	6	192	48	240	1.00	30		240	8.0
	60	7	224	108[f]	332	1.00	60		332	5.5

Note: All costs are in thousands of dollars.

[a] Based on 2 shifts of $16,000 per year per employee; includes overhead plus benefits.

[b] Based on a small minicomputer installation; includes hardware and software, amortized over 5 years.

[c] Based on several controlled experiments at Haddonfield about 1½ years ago.

[d] Based on an operating cost per vehicle per year (15 dollars per hour for a 4,000-hour year) times the difference between actual and effective vehicles.

[e] Sum of "real" control costs plus "effective" control costs.

[f] Digital communications equipment required at this level.