Economic and Reliability Trade-Offs in Dual-Mode Systems

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Reliability performance of dual-mode systems will influence both capital and operating costs and determine their public acceptability. Further, the reliability and cost balance will probably be the main determinant of which generic type of dual-mode system—integrated or palletized—is eventually selected for final development and implementation. This paper demonstrates those findings by placing reliability in the context of a total-system-worth function developed to fit the unique characteristics of the two types of dual-mode systems. In each case, interactions among reliability, availability, service level, safety, capital cost, and operating cost are traced in simplified examples based on hypothetical systems. Because of the extremely high level of reliability required of all rolling stock in the automated phase to secure acceptable system availability in close-headway operation, the capital costs are likely to be high for the palletized system. However, operating economies may offset this sufficiently to make the combination feasible. On the other hand, maintenance costs will be high for the rolling stock in the integrated system, thus casting doubt on the acceptability of the cost-availability constraint on the user.

As high-performance public service technologies move through the expensive stages of development and implementation, the interactions among reliability and economic factors exert a major and often dominant influence on the final design. This is expected to be the case with dual-mode transportation system concepts currently being explored, especially those featuring the use of small, privately owned vehicles for single-party service. This paper identifies and qualitatively examines some of these interactions and points out topics meriting detailed study as dual-mode transportation is further developed.

SYSTEM SETTING

Reliability and economic factors can be usefully studied only in the context of a physically visualizable system whose elements can be related to existing equipment and devices. The system discussed here is the dual-mode personal rapid transit (DM/PRT) system described as an analytical concept by Waddel and Roesler (1). This system is a representative and satisfactorily detailed example of conceptual DM/PRT systems—in this case, prepared as a hypothetical network serving Baltimore. This type of system is a more advanced concept and is further from being developed, perhaps, than dual-mode systems involving larger, publicly owned vehicles providing mass transportation. However, the DM/PRT system more directly addresses the purpose of acceptably preserving the societal role of the private automobile in urban regions and, thus, may be a more important conceptual approach for study.

Details of the layout and operating scheme of this system are not germaine to this discussion, but an overview of its primary dimensions and basic design options is. It is, of course, a dual-mode system in that the passenger-carrying vehicles are capable of operating in the city street network under driver control (manual phase) but can also be inserted onto an automatically controlled guideway (automatic phase) for transport through an arterial or distribution network. The concept for Baltimore consists of an arterial network connecting 29 nodes with 286.5 km (178 miles) of guideway. Local distribution networks in many of the node areas add another 78.7 km (72 miles). The system provides 1.98 million person trips per day for which an estimated 230 000 privately owned, four-seated-passenger vehicles are used. The average trip distance on the guideway portion of the system is estimated to be 10.1 km (6.3 miles), and the system experiences a daily peaking factor such that during the peak hour the system handles 52 000 vehicles. Line speeds are about 64.4 km/h (40 mph). Headway is about 1 s for independently controlled vehicles; larger headways could be achieved by training, and this option is included.

The two basically different design options to be considered in approaching a DM/PRT concept such as this one are the integrated vehicle option and the palletized vehicle option. These options relate directly to reliability considerations, and the eventual selection between them will constitute a landmark decision in the evolution of this technology. The technical and first-cost implications of these options are explored in the other study (1), but reliability trade-off issues are not directly confronted.

In the integrated option, the vehicle is equipped to function in both phases, having as permanent parts all running and control components necessary for operation on both automated guideways and streets. Since the vehicles are privately owned and maintained, this means the "system" does not directly control the state of repair of vehicle components vital to satisfactory operation on the guideway. Consequently, a necessary part of the integrated system concept is the provision of means to check out the operating condition of all vehicles entering the guideway. Equipment to do this with accuracy and speed will be a significant element of the cost of the integrated system.

In the palletized system option, the vehicles are single mode, i.e., they operate only on the street under manual control. Separate pallets, equipped to run permanently in the guideway and able to carry the single-mode vehicle, are used for guideway travel. The pallets are maintained by the system to a suitable level of reliability. This obviates the need for entrance ramp check-out of all vehicles, but introduces the cost of the pallets. For the system envisioned, 40 000 pallets would be required.

SYSTEM-WORTH FACTORS

The worth of a DM/PRT system is determined by the balance struck among its primary characteristics, effectiveness, cost, and safety. Trade-offs affecting design decisions must be made among these characteristics and the factors of which they are composed. Reliability considerations are a part of the system-worth framework as indicated below.

1. System effectiveness is based on the provision of a transportation service whose overall effectiveness can attract a sufficient number of users to justify its total costs. DM/PRT effectiveness is a function of qualities such as (a) transportation convenience (low trip time, quietness and comfort, freedom from congestion), (b) accessibility and coverage, and (c) trip dependability (availability of the system and reliability of the vehicles).
2. System safety is based on a level of achieved safety commensurate with the perceived needs of users and the proprietors of the system. This involves the elimination or control of hazards in the system such that norms associated with high-performance public transportation systems in the past will be met or exceeded. Any potential for catastrophic accidents in the automated phase of the system will have to be eliminated.
3. System costs must be acceptable to all parties that support or use the system or do both. Optimization of this system parameter is by far the most complicated aspect of technology development of dual-mode transportation whose ownership is divided between the system proprietor and the users. Costs can be subdivided into the following broad elements for consideration: (a) proprietor costs, including capital (all fixed installations plus pallets in palletized systems) and operating costs; and (b) user costs including vehicle capital costs and fares plus the usual costs of operating and maintaining automobiles.

Many trade-offs are possible and necessary in the balancing of these worth factors to arrive at a system that is both technically feasible and socially and economically useful.

EFFECTS OF FAILURES

Any significant failure in the normal operation of a vehicle will, in the closely packed guideway of a DM/PRT system, probably result in an interruption in flow for a considerable distance upstream of the failed vehicle. During peak-hour operation, the result would not be unlike the stoppages experienced on freeways when accidents block lanes during rush hours. The extent of the interruption to flow in a DM/PRT system cannot be estimated here since it will be a function of the control strategy used for the system and the time required to restore the system to normal operation (an important factor here is the time needed to remove a failed vehicle from the guideway). However, service interruption will doubtless be substantial so that failures in a DM/PRT system are likely to be "system failures" affecting the trips of a large number of users on the system at the time of the failure.

This condition is true, of course, of most PRT system concepts and is not a new problem unique to the dual-mode concept. Nonetheless, it seems to be of special significance in the DM/PRT concept since the possibility of vehicle failure, because of private-owner maintenance, is likely to be higher than will be the case in a non-dual-mode system.

The problem is further exacerbated by indications that a significant increase in the reliability of critical components over the present automotive and transit state of the art will be required. The mean time between failure for automobiles is about 500 h or 16 000 to 24 000 km (10 000 to 15 000 miles) assuming that average speeds are in the 32 to 48-km/h (20 to 30-mph) range. This corresponds with estimates of about 27 000 km (17 000 miles) for mean time between maintenance for transit equipment. If the vehicles in the system described here had failure rates of this magnitude, then the probability of failure for an average individual vehicle trip on the guideway of 10.1 km (6.3 miles) would be about 0.0004. This is an acceptable trip dependability level for an individual traveling alone in the system. However, during the peak-hour period the system would, on the average, experience 20 failures of the type described above. Although user tolerance to trip undependability is one of the still unknown factors in PRT system development, without question this kind of system failure rate is unacceptable.

A tenfold improvement in the above situation—getting the failure rate down to two per rush hour—might be an acceptable range. This implies that DM/PRT system developers must achieve reliability in the critical components of guideway-using vehicles on the order of ten times better than present levels. The impact of this kind of requirement on purchase prices and maintenance costs will undoubtedly be severe. Failure rate improvements of this magnitude have been achieved for mechanical systems in other technological fields—weapon and aerospace systems—at cost increase factors on the order of 3 to 4 magnitudes. One has to think at least in those terms when the reliability economics of DM/PRT systems are considered.

PRIMARY TRADE-OFF CONSIDERATIONS

In view of the seriousness of these reliability factors to system effectiveness, first consideration in the design of dual-mode systems must be given them. The most sharply defined design alternatives bearing on reliability are the integrated and palletized approaches. The primary economic trade-offs, then, are related to deciding between two alternatives. The trade-offs all will have to do with determining the impact of reliability costs on total private and public costs for an integrated system or for a palletized system. These trade-offs must be considered in the context of similar levels of safety and system effectiveness.

This is not to imply that the best system design will necessarily be the one offering the lowest total cost. Selecting the best option will be based on the public policy issue of distributing the capital and operating costs of this public service to the general public, through its ownership of the guideway system, and to the users, through their ownership of the vehicles. Thus, from the standpoint of system design, ways must be found by which these four elements of the total system cost can be varied with respect to one another. The identification of economic trade-off analyses stems from this basic need.

The first problem is to develop some useful information on the cost sensitivity of users to the factor of trip dependability. How much, if anything, are users willing to pay for increased assurance that a trip will be completed without interruption? Conversely, at what level of undependability will users discontinue using a system no matter how inexpensive? Until these questions are answered, we cannot proceed on a rational basis to set up the trade-offs involving reliability economics of dual-mode systems. What is actually sought here, of course, is a set of user indifference curves of cost versus dependability, all other things being equal. The set would be a family of curves representing various percentages of the potential user population to whom the system is acceptable at various cost and dependability levels. To expect that such relations could be established in any sort of rigorous manner is not reasonable; the question is too subjective. However, studies of user preferences, dependability levels, and cost structures in other modes of transportation—especially automobiles—might shed enough light on the subject to permit the making of a set of estimates that would form a framework for a rational investigation of system reliability trade-offs.

When such a framework is established, the relations between vehicle reliability and trip dependability will have to be found for chosen versions of both integrated and palletized systems. This will exercise the basic options directly in reliability terms. Versions of the palletized system to be examined would involve various reliability levels for pallets and other operation-critical subsystems (controls, propulsion). However, because of the nature of the design of the palletized system, little interaction will probably be found between vehicle reliability and trip dependability. That is, the vehicle reliability will completely determine the dependability of the street portion of a given trip, but the guideway system reliability will control that of the automatic portion independently of the vehicle. Thus, "street reliability" of a state-of-the-art vehicle should show up as producing a satisfactory level of trip dependability if the guideway system and pallets are good enough.

Conversely, the trip dependability of the integrated system is completely controlled by vehicle reliability while on the guideway. The inspection equipment needed as a part of this system concept will probably be able to check the operating condition of vehicles entering the system but not the imminence of failure. In other words, inspection equipment will not check the reliability of vehicles moving into the system—reliability will still be a function of component quality and level of maintenance. Thus, the variation of trip dependability with differing levels of vehicle reliability must be established—again, as a function of a variety of system options.

One option to be studied in this connection is a system design providing immediate removal of failed vehicles from the line to prevent system outages because of a single-vehicle stoppage. Although this option could be applied to both system design approaches, it seems especially pertinent to the integrated system. It would not be simple to provide. Twice as much guideway width would be required to provide space to put stopped vehicles at any point along the way, and the added complexity in the control system for automatic removal would be severe. Nonetheless, this option (a trade-off between system cost and vehicle cost) should be explored.

Once a set of relations are established between vehicle reliability and trip dependability levels for both types of systems, the trade-off analyses can be directed toward balancing capital and operating costs at different levels of vehicle and system component reliabilities. The variations will be controlled mainly by component quality factors versus levels of maintenance. Here, again, a sequence of design options at the subsystem or component levels should be invoked as a part of developing the trade-off continuums.

The possibility exists, and would be discovered at this point, that the user cost levels involved for one or both systems may be so high that a finding of infeasibility (relative to user needs discussed previously) can be confirmed. For example, it is plausible to expect that the user cost in the case of the integrated system will turn out to be unacceptably high no matter how the balance is worked out between capital and operating costs. As a case in point, the study by Waddell and Roesler (1) estimates a first cost per vehicle of $5000 for the integrated system case. The cost increment over the cost of a conventional automobile of equivalent capacity and driving characteristics is about $1000. This is intended to account for the additional control and propulsion equipment needed for running on the automatic guideway. There is no allowance for the higher quality needed in the vital subsystems to provide something like a tenfold improvement in reliability over conventional automobiles. The burden of ensuring this kind of operational reliability is thus placed on the user's own maintenance program.

This option appears bound for failure. There can be no element in this system that constrains entering vehicles to be in a satisfactory state of reliability. Ramp inspection equipment can at best be expected to check operability; a poorly maintained vehicle will usually be passed if all the vital subsystems happen to be functioning correctly at the moment of inspection. Potential for failure once on the guideway will be largely undetected. Thus, the burden of reliability performance will be on each of the individual owners, who must be willing to carry out what will undoubtedly be an expensive regime of inspection and preventive maintenance. This cannot reasonably be expected to happen—at least, not sufficiently so to be the base of the success of a major transportation system network. The only other option that appears to be available is to build in the reliability level at a heavy first-cost penalty. The negative reaction of the automobile market to heavy first-cost penalties need not be elaborated on here.

The comparison by Waddell and Roesler (1) of the integrated and palletized systems showed a probable advantage accruing to the latter on first-cost issues alone. The line of intuitive reasoning above supports this finding in the area of trade-offs of reliability and economics. The extremely tentative nature of these findings—especially the latter—is obvious. Serious design work must be undertaken before calculations of cost trade-offs that have decisive credibility can be made. The community of firms and agencies involved in the development of dual-mode transportation technology may usefully develop guidelines that will lead to an early and convincing resolution of the issue.

REFERENCE

1. M. C. Waddell and W. J. Roesler. Analyses of Some Dual-Mode Personal Rapid Transit System Operations. Applied Physics Laboratory, Johns Hopkins University, Rept. CP-020/TPR024, Sept. 1972.