Comparable Systems Analysis of San Francisco's Bay Area Rapid Transit System: Lessons for Automated Highway Systems

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This study examines the lessons to be learned from the experience of the San Francisco Bay Area Rapid Transit (BART) system, particularly as applied to the growing research on automated highway systems (AHS). By examining the technical and nontechnical issues surrounding the development and implementation of BART in the 1960s and 1970s, the insights gained may be applied to future research and ultimate deployment of AHS. The first section of the report describes the analogy of BART by comparing some of the technical and nontechnical performance factors surrounding AHS and BART. Several pertinent technical and nontechnical issues surrounding BART are described in more detail, emphasizing the decision making that went in to BART's development, testing, and opening for revenue service. Several key issues are pursued in detail. Technically, the issues of safety, reliability, and maintenance were identified and investigated. It appears that sound system engineering principles were not applied in the BART case, and specific recommendations for improving this practice for AHS are described. In addition, the nontechnical issues of political pressure and loss of public confidence are also investigated. In this case, these pressures have severely hindered BART from achieving its full potential. The insights from the BART experience are directed toward improving the planning, design, development, and ultimate deployment of AHS.

The FHWA, as part of a recent broad agency announcement, commissioned a precursor systems analysis of the technical and nontechnical issues surrounding automated highway systems (AHS). Part of that research included an analysis of comparable systems to summarize the lessons learned from similar experiences with new technology. By reviewing these lessons, we may avoid the mistakes of the past and also make better decisions for the development and deployment of AHS. Below, the basic tenets of an AHS are outlined and the choice of San Francisco Bay Area Rapid Transit (BART) system as a comparable system is described. [In this report, BART refers to the rail transit network and its operation. The organization that runs the transit system is the Bay Area Rapid Transit District (BARTD).]

AUTOMATED HIGHWAY SYSTEMS

The basic operational concept for an AHS is that many of the typical driver functions are automated, primarily the control of steering, throttle, and brake, allowing "hands off, feet off" driving. Generally, an AHS involves an equipped vehicle and a reserved right-of-way.

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There are a number of technical and nontechnical issues associated with automated driving. Technically, there are issues associated with the sophistication, accuracy, and reliability of vehicle control. To this end, many technical needs have been identified, including:

- Proximity sensors/detectors,
- Vehicle lateral control (steering),
- Vehicle longitudinal control (throttle and brake),
- Coordination of maneuvers with other vehicles (lane changing, merging),
- Transition into/out of automated driving from/to manual driving,
- System safety in normal and degraded service conditions,
- System reliability,
- Communications requirements, and
- Response to degraded service conditions (e.g., vehicle breakdowns, accidents).

Perhaps greater than these significant technical issues are questions about the implementation and public acceptance of AHS, including:

- Ability to solve traffic congestion,
- Ability to solve safety problems,
- Environmental impacts (emissions, right-of-way requirements, etc.),
- Coordination of infrastructure provider (public) with vehicle provider (private),
- Public acceptance of the technology and of the loss of manual driving control, and
- Public response to accidents and other major problems.

These technical and nontechnical issues may appear very daunting, but many believe that an AHS is feasible. The U.S. Department of Transportation is sponsoring a national AHS consortium to identify possible solutions. With an investment of $210 million over the next 7 years, this consortium represents a considerable research and development effort. As we enter this intensive effort, it is important to review the lessons learned from other comparable experiences.

Why BART?

There are several factors that suggest that the BART system may be reasonably comparable to an AHS, including:

1. Interaction with the public. BART represents a comparable transportation system, in which the urban public is given a new transportation alternative. Currently, BART carries 260,000 trips per day. As a new transportation alternative, AHS may also face high utilization by the public.

2. Degree of intelligence. BART train operation, control, and supervision are fully automated. Train movements are under centralized control using sophisticated signals and communications. An AHS will also incorporate a high degree of intelligence.

3. Severe safety constraint. There were considerable safety issues associated with full automation of BART: train control in accident or emergency situations, hazards associated with car-borne components, safety of passengers, failures of train and central control systems, and other infrastructure failures. There are also considerable safety implications with automated vehicle control within an AHS.

4. Severe reliability constraint. Under full automation, BART has considerable reliability constraints: maintaining train schedules, interpreting speed commands, maintaining safe distances between trains, sensing the location of trains, and coordinating train movements. As with BART, the complexity and accuracy of vehicle and system-wide control systems will help determine the reliability of an AHS.

5. Many diverse subsystems. Many subsystems are required for BART, including car-borne, wayside, infrastructure, and central control systems. These subsystems manage train propulsion, operation, detection, signaling, and central control. AHS also will involve a comparable set of diverse sub-systems.

6. Failure modes. Failures in the automatic train control and train detection systems have resulted in several well-publicized accidents on BART. Subsystem failures require the removal of trains from service and associated disruptions. Vehicle and infrastructure system failures are also possible for an AHS and may significantly impact public perceptions of this technology.

7. Outage time constraints. Safe and prompt response to service disruptions are necessary on BART. Although fail-safe principles apply, continued operations under degraded service conditions are critical to system performance. For an AHS, operation in periods of system failures and degradation must be critically examined.

Based on these factors, the BART experience is examined as a comparable system to derive insights for AHS development and operation. Section 2 highlights a preliminary investigation of the key technical and nontechnical issues surrounding BART's development and draws some insights for AHS. The third section describes a detailed analysis of several key technical and nontechnical issues, making specific recommendations for AHS based on the BART experience. A fourth section offers a few conclusions.

PRELIMINARY DISCUSSION

A review of the literature regarding the planning, development, and operation of BART was conducted, yielding a set of salient issues that are particularly relevant for the continuing development of AHS. This section summarizes these technical and nontechnical issues from BART.

Technical Issues

Level of Technical Sophistication

In the 1950s, BART represented an opportunity to capitalize on new technologies. In order to lure travelers, planners envisioned a high level of service, with headways of 90 sec between trains and top speeds of 128 kph (80 mph). One such technology to reach these goals was an automatic train control (ATC) system. At that time, there was little opposition to this technology, although it was untested when the choice of technology was made. BART represented an opportunity to bring train control systems into the 20th century using more sophisticated vehicle detection, communication, and train control technologies. Similar choices about the sophistication of vehicle and roadway technologies are pending for AHS.

Level of Technical Verification and Testing

Having chosen advanced train monitoring and control technologies, BARTD and the prime contractor (the team of Parsons-Brinckerhoff, Tudor and Bechtel, or PBTB) developed specifications for these systems. However, contracts for the technical systems were not always awarded to contractors with appropriately tested and proven technologies. For example, the ATC contract was awarded to the lowest bidder (Westinghouse Electric) based on a design that was not previously demonstrated. Also, before revenue service, each car-borne and wayside system was to undergo substantial testing and quality assurance; however, these standards were not rigorously maintained, largely because of project delays. Similar specifications for AHS systems will be developed, and a rigorous program of verification and testing for these AHS systems is needed.

Consideration of Safety and Reliability

In the legislative act creating BARTD, the California Public Utilities Commission (CPUC) was given authority to monitor the safety of BART operations. The CPUC had little experience with transit systems and provided very little oversight during the early years of system development. In general, there were few safety standards included in the original system specifications. Moreover, PBTB and BARTD did not have any safety, reliability, or systems engineers on the project until the early 1970s, as BART moved into prerevenue operation. However, a large number of safety problems surfaced during system testing, including: unintended station run-throughs at 80 kph (50 mph), large gaps between cars and platforms, and a lack of information displays for the train operator. Also, there were considerable reliability problems with the ATC system during the early years of operation. For an AHS, safety and reliability will be critical to successful operation.

Other Shortcomings in Technical Performance

Original expectations of 90-sec headways through San Francisco and Oakland, with peak speeds of 128 kph (80 mph), have not been met, largely because of safety problems with the ATC system, train and car reliability problems, lower than expected acceleration and deceleration rates, and considerable control delays at track junctions and endpoints. Moreover, BART operations have shown little tolerance for service degradation. First, there was little consideration for a means of conveying information to the train operator in normal or degraded service (e.g., location of train system malfunctions, speed limits, block occupancies). Second, there were severe limitations on degraded system operation, restricting train speeds below 40 kph (25 mph) and requiring significantly longer clearances (headways) between trains. These problems caused significant disruptions to service, especially during the first several years of operation. These observations suggest more concerted examination of AHS operations in degraded service conditions.

Maintenance Requirements

BART's experience reinforces the supposition that higher technology leads to higher maintenance costs. Studies comparing BART with other rail transit systems suggest that the operating personnel and expenditures saved through system automation are less than those required to maintain the system. Initially, many problems attributed to maintenance were, in fact, because of poor workmanship and quality control of car systems. Also, BARTD lacked the know-how within the maintenance staff to deal with car problems, resulting in high dependence on the car supplier (Rohr). The maintenance requirements of infrastructure and vehicles for AHS should likewise be identified and addressed.

Nontechnical Issues

Level of Expectations

At its inception, BART was intended to be a panacea to the problems of urban sprawl, decentralized commercial activity, and traffic congestion. Planners believed that BART would focus development in the urban core areas of Oakland and San Francisco. However, research to date suggests that BART has had little impact on commercial activity in Oakland and San Francisco and has done little to alleviate traffic congestion. There are similarly high expectations for an AHS system that should be critically examined to determine their credibility.

Public and Private Responsibilities in Development

BARTD selected PBTB for both the system design and construction management and awarded a cost plus fees contract. PBTB was answerable directly to the BARTD board of directors, leaving little oversight from BARTD staff to manage PBTB's costs or engineering practices. Moreover, there was little technical experience in rail transit systems among personnel at BARTD, leaving much of the technical oversight with PBTB. PBTB also managed all of the system subcontractors, many of whom were traditional defense contractors with little or no experience in public transit. In this way, the BART project blurred the roles of public agencies and private firms. AHS will likely bring both public and private interests into project development, and responsibilities of each should be clearly defined.

Political Pressure

BART ran over budget and opened for revenue service much later than expected for a variety of reasons: construction problems, contract negotiations and disputes, technical problems in prerevenue testing, and securing of additional project funding. Significant political pressure, however, brought the system into revenue service before the full system was operable and before all technical components had undergone sufficient testing. As a result, significant degradation in service and several accidents marred the first few years of operation. AHS will also come under significant political pressure to begin operation, and this pressure must be dealt with appropriately.

Market Prediction

Actual ridership on BART was much lower than forecast. Figures for 1975 generally show BART daily ridership at 51 percent of the forecast value (133,000 actual versus 260,000 forecast). Even today, ridership levels are lower than originally planned. Some reasons for this shortfall include: lack of rigor in the forecasting methodology, unanticipated growth in automobile ownership and low gasoline costs, poor station access, and public concerns for system reliability and safety. Similarly, caution is necessary in predicting public acceptance and demand for AHS.

Loss of Public Confidence

During the early years of BART operation, there were significant delays and disruptions in service, mostly because of problems with the ATC system and other car-borne and wayside systems. Also, several accidents were attributed to system failures or poor operating procedures, resulting in much negative publicity. Coupled with significant financial problems in the first several years, these factors led to a loss of public confidence in BART. The public perception of BART has only slowly recovered from these initial setbacks. As with other high-technology systems, AHS will also face considerable early scrutiny of system performance, and the handling of initial setbacks may determine the ultimate success of AHS.

DETAILED DISCUSSION OF BART ISSUES

The following section discusses in greater detail the technical and nontechnical issues of greatest interest and similarity with current AHS issues. The first section discusses the technical issues of safety, reliability, and maintenance (Items 2, 3, and 5 from the technical issues list above), while the second section details the nontechnical issues of handling political pressure and the loss of public confidence (Items 3 and 5 from the nontechnical issues list).

Technical Issues

Before going into the specific issues of safety, reliability, and maintenance, it is important to make some general observations about BART's technical development process. During development of the technical systems in the 1960s, the role of BARTD was intentionally primarily managerial as opposed to technical. PBTB, as prime contractor, was responsible for system integration and technical oversight. It was not until the system went in to prerevenue testing that many technical responsibilities shifted from PBTB to BARTD. As one can note, many of the pitfalls noted below fall in the gray area of technical responsibility between PBTB and BARTD, often during this critical time just before BART opened.

The delegation of virtually all technical development tasks to PBTB meant that there was little oversight by BARTD staff. This is widely considered to be the most significant error in the development of BART [e.g., see Burck (*1*,p.105); Profet (*2*,pp.124ff); and Legislative Analyst, State of California (*3*,pp.51ff)]. The primary problems did not stem from poor technical choices; rather, their root cause lay in poor project management and oversight by BARTD. It is noted that up until the late 1960s, only one member of BARTD staff was an engineer, and he had served as a consultant to PBTB in some of their BART work before his appointment at BARTD. Thus, there was little review of PBTB's technical work, either by BARTD or an independent review board, during critical times in the development process.

Recommendation

In the development and procurement of an AHS, a competent and independent technical review team should be retained during each phase of technical development and system testing. Also, the operating organization should hire capable technical personnel from the early stages of system development.

There are several other characteristics of BART that deserve mention. First, through the technical development process, BARTD and PBTB lacked any individuals specifically assigned to systems engineering or integration. Although such systems engineers are common in detailed aerospace technologies, they are rare in transportation. During the development of new technical subsystems, a systems engineering function at BART would have aided in integrating vehicle, wayside, and central systems; anticipating system hazards; and responding to system problems.

Recommendation

In program development, as well as in each field operational test and proposed implementation, a systems engineering function should be incorporated that integrates AHS subsystems for the vehicle, wayside, and infrastructure.

Second, PBTB chose to use functional rather than design specifications for the development of several technical subsystems. These specifications allow characterization of a system in terms of its function, rather than determining detailed design standards, and allow the greatest innovation by the system developer. In the BART experience, examples of liberties in design include the novel train control system, the car design (by an aerospace contractor), and a nonstandard gauge and concrete ties for the track to improve ride stability. However, this type of specification makes it difficult to verify contractual obligations of each system contractor when the system does not perform as desired; BARTD entered litigation separately against Westinghouse and Rohr over the issue of system specifications and the resulting contractual obligations (*4*,p.144; *1*,p.105). In addition, the high degree of innovation in design may also lead to difficulties in system integration.

Recommendation

AHS specifications must carefully balance the need for technical innovation with the need for more specific design criteria to assure a safe and reliable system.

Safety

During the first several years of operation, BART was plagued with safety problems. Many of these problems resulted not from operator error but rather as the result of technical faults. Several safety issues emerged in prerevenue testing as many of the technical bugs were worked out of the system. This period of testing, however, was cut short, resulting in safety problems in revenue service that received high publicity (*4*,p.8).

The first major accident in revenue service occurred only 3 weeks after the system opened in 1972. According to the investigation by the Legislative Analyst, State of California (*3*,pp.25ff), the carborne ATC equipment misinterpreted a speed command, causing the train to speed past the Fremont station and crash at the end of the line. In January 1975, a nonrevenue train had a fatal collision with a maintenance vehicle; the accident was blamed on the inability of the train detection system to detect maintenance vehicles on the main right-of-way. A third serious accident in 1979 involved a train fire in the Transbay Tube. Further investigation revealed that the material from which the cars were manufactured was not sufficiently flame-retardant.

These incidents raise specific concerns about the treatment of safety by BARTD and PBTB because these problems were primarily because of technical error. It seems that the root causes of these safety problems resulted from several factors in the system development process (*4*,p.85). The following describes these factors and identifies some lessons learned about the treatment of safety for the technical development of AHS.

1. Specification of safety requirements for system components. The system specifications put forth by PBTB for each of the technical systems were primarily functional and not design specifications. In using this approach, specific safety standards for each proposed new technology were basically nonexistent: the technology for critical subsystems (such as the ATC system) lacked widespread industry safety standards (*4*,pp.166–167).

Recommendation

Regardless of the decision for functional or design specifications, safety and reliability requirements for system operation should be explicitly incorporated.

2. Hazard analysis of the system. Because many of the subsystems were developed as new technology, it would have been helpful to have a systems engineering function to determine appropriate ways of integrating these subsystems. One part of this function would be a complete hazard analysis of the various system components and possible modes of failure. Oddly, a hazard analysis was performed on the car-borne and wayside ATC equipment in 1971, and it identified several critical deficiencies in system design, including possible misinterpretation of speed commands on the vehicle (*5*,pp.169–170). Unfortunately, PBTB had not investigated this matter further before the related accident during revenue service in 1972 (*5*,pp.232–233; *3*,pp.27–28).

Recommendation

A critical function of systems engineering for AHS should be a detailed hazard analysis of vehicle, wayside, and infrastructure systems. This hazard analysis must be performed as early in the design process as possible to allow revisions to the system design.

Recommendation

Safety issues should be given highest priority in determining the readiness of an AHS system before start of service.

3. Technical experience at BARTD and the CPUC. The CPUC was given responsibility for assuring safe operation in BARTD's enabling legislation in 1957. However, PBTB controlled technical system specification and development up until the system opened for revenue service. Personnel at both BARTD and the CPUC during the 1960s and early 1970s had little experience with rapid transit systems or their associated technologies (*3*,pp.37–45). Both agents may have been aided by hiring technical personnel much earlier in the technical development process.

Recommendation

A staff of technically competent safety engineers should be hired (or retained) to conduct independent safety analyses for an AHS. This staff should be brought in to the AHS development process as early as possible.

4. Organizational treatment of safety within BARTD. Up until April 1972, a few months before the system opened, safety engineering was only a small organization within the operations department and relied heavily on the technical expertise of the operations and maintenance personnel. To many, this did not allow a fair and independent safety review, because the operating personnel were under considerable political pressure to bring the system into revenue service (*3*,pp.43–45). In May 1972, the safety group was moved under the finance department, creating a new insurance and safety organization that was thus free of the political pressure but nonetheless distant from the technical expertise of operations and maintenance. In 1973, the group was moved up to the departmental level (the insurance and safety department), largely because of political pressure resulting from the revenue service accident and other studies of system safety (*3*,pp.43–45). The technical competence of the safety group was still inadequate, leading BARTD to retain the Lawrence Berkeley Laboratory as safety consultants for several years after beginning revenue service (*6*,pp.11ff). It was not until July 1975 that an independent safety department was formed at BART (*7*,pp.20–21).

Recommendation

A safety engineering function should include staff members at the highest possible level within the AHS development team, who can effectively communicate safety concerns to project management.

5. Capabilities of a safety program. Now that BART has been in operation for over 20 years, the safety department has been given considerable responsibility and broad authority to improve safety within BARTD. The responsibilities of the BART safety program now, as detailed in the following list, may be transferable to an AHS safety organization (*8*,pp.15–16).

- Setting reasonable safety goals and objectives for BARTD.
- Informing BARTD management of safety status, problems, and improvements.
- Participating in the planning and review process for system design, construction, reliability, maintenance, and personnel training.
- Reviewing engineering tests to ensure compliance to safety requirements.
- Monitoring and inspection of system operation.
- Conducting hazard analyses to identify and mitigate safety risks.
- Analyzing operating rules, procedures, and practices to limit exposure to hazardous situations.
- Collecting and reviewing historical information on hazards, system failures, and accidents.
- Investigating system failures, mishaps, and accidents.
- Ensuring operability of hazard detection and warning systems.
- Ensuring compliance with regulatory agencies.
- Organizing and coordinating safety programs within BARTD.
- Conducting scheduled and unscheduled disaster and emergency exercises and drills.

Reliability

Because many of the subsystems in BART relied on new technology, system reliability was a significant issue in system development and early operations. The facts of the BART experience are clear: during this time, major reliability problems emerged. As late as 1975 (3 years after opening for service), an average of 40 percent of BART cars were out of service on a given day because of failed components. Car-borne system failures occurred very frequently in revenue service, seriously degrading train and network-wide performance. Failures in the wayside ATC system also caused considerable delays. In time, however, BART has been able to recover from many of these early reliability problems but not without generating considerable public dismay over system performance.

AHS, because it represents an entirely new technology, has very severe reliability constraints associated with successful deployment. In contrast with BART, however, an implementation of AHS may come under significantly greater pressure to ensure a high level of safety and reliability in early operation. Also, AHS may not be so fortunate to have a long "grace period" to work out the bugs in the system; perhaps today's public is less forgiving and patient. To this end, the following issues in system design and development may serve as learning experiences from BART.

1. Design for "graceful decay." BART was intended to be, and ultimately achieved its goal, a completely automated train operation, even under degraded conditions. However, during the first several years, operating procedures for degraded conditions resulted in significant disruptions in service. Statistics from the first 3 years of operation show that passengers had to be off-loaded for one of every four equipment failures, a measure at least seven times worse than other peer rail transit systems. Moreover, during any single carborne failure, "fail-safe" procedures were applied; in almost all cases, this implied a full stop of the train, after which the train was limited to a maximum speed of 40 kph (25 mph). Because there are few yards or sidings on the BART system, these trains would continue over a significant portion of the network at this reduced speed. These frequent stops and speed restrictions resulted in serious delays that propagated through the system (*9*,p.IV–14).

Recommendation

Consideration of automated systems should focus on a graceful decay under degraded conditions. System specifications for AHS should focus on design for possible service degradation, including equipment malfunctions in the vehicle, at the wayside, and in the infrastructure.

2. Design for human interaction. As originally designed, the train operator is responsible for operation only in the case of a major service disruption or emergency. However, because the ATC system was not fully operational when BART opened for revenue service and because service disruptions occurred frequently, the operator played a more significant role during the first few years of operation. This role was impeded by a cab design that assumed a much more passive role of the operator: there were no information displays in the cab for the operator to know the intended vehicle speed or information on subsystem failures within that train. As a result, operators used line-of-sight rules for train operation or held trains in a station for extended periods to locate car problems. This was a serious design flaw that led to substantial train delays in early revenue service. It was several years after beginning operation before the cab interfaces were upgraded (*9*,p.II–7 and III–3; *4*,p.157).

Recommendation

An AHS design must be sensitive to the information provided to drivers during automated operation, especially during degraded conditions. Human factors research should emphasize the driver's response to information, especially in degraded service or emergency situations.

3. System specification and development. With some federal financial assistance, PBTB developed a test track to test alternative system configurations. The track ultimately had two purposes: to allow prospective system suppliers to test their products and to assist BARTD and PBTB in developing specifications for each of the required subsystems (*4*,p.141). Many suppliers participated in the testing program. Moreover, PBTB often incorporated the abilities of several products tested on the track in developing the functional specifications for subsystems. This testing program was very successful, considering the lack of research and development on these systems nationally at that time (*4*,p.152).

In deciding on contract awards, however, the testing experience was largely ignored (*4*,p.152). Because the specifications were functional, subsystem design was left to each contractor. Moreover, contract award criteria were independent of whether vendors had successfully demonstrated their product either on the test track or in any other application. As a result, many of the contracts were awarded to suppliers with little experience or no proven product. For example, the contract to supply rail cars was given to a supplier with no experience in rail transit, and the ATC system contract was awarded to Westinghouse Electric in spite of the fact the proposed system had never been tested and no prototype existed.

Recommendation

As much as possible, AHS operational test sites should be flexible to allow various manufacturers to test new technologies. In selecting system suppliers, technical experience, proven technology, and test results should be given considerable weight in the evaluation criteria.

4. Prerevenue system testing and quality assurance. BARTD had no internal quality control organization for the delivered systems (*10*,p.6). As a result, operating and maintenance personnel at BARTD relied heavily on PBTB for early product testing and quality control. Simultaneously, political pressure was mounting on PBTB to bring the system into revenue operation; construction delays had already pushed back the opening for revenue service from 1969 to 1972. For this reason, testing and quality control functions were rushed, leaving considerable doubt regarding the effectiveness of test procedures (*4*,p.149). One report indicates that less than one-half of the rolling stock had been subject to adequate yard departure testing, and none of the cars had undergone complete ATC system tests, before revenue service began (*3*,p.69). This inadequacy of system testing also had significant repercussions for the maintenance function at BARTD.

Recommendation

Sufficient time in the AHS development process must be left for product testing and quality control. This involves allowing ample time and resources for suppliers to debug new technical subsystems and to test and debug the fully integrated AHS on site before beginning operation.

Maintenance

Maintenance was the responsibility of BARTD once the various contractors began delivering each of the subsystems. The maintenance organization within BARTD's operations department was responsible for checking car-borne systems on arrival of the car at the yards. However, the maintenance department relied heavily on PBTB to supervise these testing procedures (2,pp.78ff). Once revenue service began, BARTD alone was responsible for approving trains for release into revenue service each day. Because many of the delivered subsystems had not been adequately tested, the maintenance function faced a considerable workload once the system opened. Anywhere from 30 to 60 percent of the cars were in the shop on a given day, and about 25 percent of the cars were brought into the shops three or more times with the same problem (*6*,p.17; *11*,p.III–22).

Several factors that influenced the planning and management of maintenance at BARTD offer insights for AHS.

1. Design for maintenance. In terms of component specifications, PBTB took a novel approach by including reliability, maintainability, and availability (RMA) specifications directly. Despite this approach, a number of contractors did not adequately consider product failures and maintenance requirements in designing their systems. For the cars, critical train control systems were located in very troublesome positions on the car, requiring significant time to repair or replace. The car manufacturer also did not adequately consider some of the environmental hazards of rail operations; for example, several critical components were mounted on the undercarriage, where there is considerable wear and tear in normal operation (*12*,p.331). On the other hand, some components were too accessible. For example, the emergency door release equipment was placed just below a passenger seat and attached only with Velcro brand fasteners. Thus, a passenger might accidentally (or deliberately) open the doors while the train was in motion (*10*,pp.113–114). Such problems required considerable work to modify the location of components.

Recommendation

RMA specifications should be used for any AHS implementation, including explicit mean-time-between-failures and mean-time-to-replace requirements. These requirements should be specified for both vehicle and wayside equipment, ensuring that parts are easily accessible and that component trouble-shooting requires minimal effort, both on board the vehicle and in the automated lanes.

2. Maintenance information. Initially, BARTD maintenance personnel were very dependent on PBTB and its subcontractors, largely because the system specifications had been developed by PBTB and ultimate product designs were approved most often without adequate oversight by BARTD personnel (*2*,pp.78–80). Another significant problem with BARTD's maintenance efforts in the early years can be attributed to a lack of information about the systems built: significant discrepancies were often noted between car-borne systems as delivered and the blueprints on hand at BARTD. Information was inadequate, placing additional demands on the contractors to assist with maintenance (*2*,pp.27–34). The maintenance effort was also poorly managed within BARTD: there was initially no consistent information reporting format to identify problems on cars as they were brought to the shops, making it difficult to know the type and severity of the problem (*2*,pp.87ff).

Recommendation

AHS system operators should develop substantial maintenance capabilities in house during system development. Because of the large number of diverse subsystems involved with an AHS, capabilities must include a common information system to track component specifications, performance, and failures.

3. Maintenance planning and management. In addition to the information reporting problems noted previously, initially there were inadequate supplies of common parts. This resulted primarily from the management's inexperience with traditional inventory stocking practice (*11*,pp.III–40ff). Also, because of the magnitude of initial system problems, resources were not managed effectively; because of the great need to keep rolling stock on the rails, resources were funneled into crisis management, detracting from detailed trouble-shooting or other preventive maintenance practices (*11*,pp.III–24ff). During one maintenance audit, the ratio of hours spent on unscheduled versus scheduled maintenance was 1.48:1 (*10*,p.4). As a result, problems were not adequately diagnosed, and cars often returned to the shops with the same problem as a previous visit.

Recommendation

The provision and maintenance of in-vehicle components will obviously be the responsibility of equipment suppliers; these suppliers should carefully consider maintenance requirements in designing and developing these systems. Infrastructure providers should also begin planning for maintenance requirements during the development process. In both cases, requirements will include maintenance equipment to identify and repair failures, common information systems, and clearly defined procedures for addressing scheduled and unscheduled maintenance needs.

Nontechnical Issues

The success or failure of large public projects such as BART is typically driven not by the level of technical sophistication but rather by nontechnical issues. The political conditions and overall public perception of the project may have significant ramifications for its success, especially if there is a large investment of public money in a project. The challenge to the project management is to deal with these pressures appropriately. The BART experience suggests that if the these concerns are not handled appropriately, the project faces an uphill battle for political and public acceptance.

In public transit projects, the loss of confidence either in the political realm or among the public at large rarely results in the full project being canceled. In the BART case, although mistakes were made in the development process and in the early years of operation, system operation and ridership have improved significantly. This ability to tolerate short-term problems for long-term benefits results in part from the long-term success of other cities' rail systems (Boston, New York, Chicago, etc.). For AHS, however, no such long-term experience with the technology exists, and the early years of AHS implementation will be critical to the acceptance of this technology. Thus, alleviating the early political and public acceptance issues is important to sustain long-term development of AHS.

Political Pressure

The political stakes in BART during the early 1970s were the culmination of a political process beginning more than 20 years earlier. The genesis of BART was the result of strong political forces in the Bay Area in the 1950s, when BART was sold as the core element of the regional planning program (*13*,pp.3–5; *14*,pp.10–11). Politicians and the business community supported the rail system because they thought it would solve the problems of urban sprawl, decentralized development, and increasing traffic congestion. Thus, the political forces were sold on rather unrealistic expectations of what the rail system might do (*13*,pp.7ff).

The resulting political energy was compounded by the large number of actors involved, including:

- Local officials,
- The BARTD board of directors,
- The regional planning commissions: the Bay Area Rapid Transit Commission (1951–1957) and the Metropolitan Transportation Commission (since 1970),
- The California state legislature,
- The Federal Department of Housing and Urban Development (HUD), and
- The Federal Urban Mass Transportation Administration (UMTA).

The California legislature created BARTD in 1957 and provided some funding for the project through the 1960s, whereas HUD and UMTA provided funding for the BART system development in the late 1960s and early 1970s. Thus, many political interests had a financial or political stake in the success of BART.

As with most public works projects, delays were considerable. The initial starting date was pushed back from 1969 to 1972, and the Transbay Tube was not opened for revenue service until 1974. In the late 1960s, delays were primarily related to the final systems design, procurement, and funding (*14*,pp.21–22). Yet, technical concerns and procurement problems with the ATC system and the cars contributed significant delay in the early 1970s (*3*,p.12). Political pressures mounted to begin revenue service as early as possible.

The high political expectations, the many institutions, and the inevitable project delays all resulted in great political pressure on BARTD and PBTB. Several measures, detailed in the following list, may have either contributed to or alleviated some of this pressure.

1. Interaction of technical and political forces in the development process. During the 2 years before opening, delays resulted primarily from technical problems with delivered systems. Most researchers believe there was insufficient time to work out these bugs before BART entered revenue service. Unfortunately, the technical personnel on the project (primarily at PBTB) either were not in a position to influence decision making or simply did not speak strongly enough for a longer testing period. It seems that there was inadequate representation of technical concerns in the political process, attributed to the poor management of technical issues at BARTD (*1*,pp.106–107).

Recommendation

Technical personnel should maintain high visibility in AHS decision making throughout the development process. Administrative and management boards should include staff with a high degree of technical competence.

2. Ability to develop the system incrementally. One advantage of the radial nature of the BART system design is that it permitted incremental implementation. BARTD was able to open the Fremont-Oakland line first in September 1972, alleviating at least some of the pressure to bring the system on line. This early operating experience could also be translated to other lines before they opened for revenue service. Political pressure was obviously greatest to open the Transbay Tube between Oakland and San Francisco [e.g., see the emphasis in Legislative Analyst, State of California (*3*,pp.12–13)]; unfortunately, that section was the last to open in September 1974.

Recommendation

As system design will allow, AHS projects should take advantage of incremental implementation. This may imply that an AHS be deployed in a small corridor initially, allowing for system expansion to other corridors in the future. The selection of an initial corridor should be based in part on that corridor's ability to demonstrate significant first user benefits.

Loss of Public Confidence

From the seemingly strong voter support in 1962, public opinion on BART deteriorated. Public relations activities during the development and construction were minimal. Also, in the first years of revenue service, passengers found the stations difficult to get to and encountered frequent delays and disruptions in service. These problems were compounded by the state legislature's discovery of widespread system safety and reliability problems after the system opened [reported in Legislative Analyst, State of California (*3*)]. As a sign of this loss, BART ridership is just now reaching levels initially predicted for 1975.

In hindsight, several factors contributed to the deterioration of public support for BART.

1. Level of public interaction before opening. Following the voters' approval of a bond bill in 1962, contact between BARTD and the public diminished rapidly, because of, in part, the obvious shift in focus toward design and construction and away from consensus building (*15*,p.49). However, communities could hold public hearings at any time after the vote; sadly, few communities took advantage of these, except where there was considerable opposition to development plans [e.g., Berkeley, summarized in Zwerling (*15*,pp.56–65)]. Moreover, responsibility for public relations passed from BARTD to PBTB, despite the fact that the contractor had little expertise in this area (*14*,p.22; *15*,p.43). Moreover, little effort was made by PBTB to solicit public comment during design and construction for fear this would contribute to additional delays and costs (*14*,p.45; *15*,p.49).

Recommendation

AHS project development should include mandatory public forums to discuss system implementation, both before initial project authorization and during the project design and construction. Also, other public information strategies should be implemented, such as local site offices, telephone information lines, and other forums for public information and feedback.

2. Public perception of the ease of use. From the initial system design, access to BART was difficult because of the large interstation spacing. The system needed substantial in-station parking and feeder bus service to provide station access for both drivers and transit-dependent passengers (*13*,pp.33–34). However, parking facilities were and remain inadequate to handle demand. For the feeder bus service, BART was largely unable to coordinate services with local providers such as AC Transit and Muni. Although there were clearly stated policies regarding service coordination between BART and these transit providers, little actually changed once BART opened (*15*,pp.91–104). For example, BART is still competing with AC Transit for passengers traveling across the bay. These problems may have resulted in part because BARTD was not responsible to any regional transportation planning body during development in the 1960s (*14*,p.45).

Recommendation

AHS should be incorporated in a regional transportation planning process (likely to be mandated under current federal legislation) and should be coordinated with other regional transportation system improvements. Specifically, adverse and beneficial impacts of an AHS should be addressed in the context of the entire regional transportation system.

3. Overcoming early problems. Finally, BARTD officials were not candid with the public about early problems on the system, including service delays and disruptions. Statistics compiled in 1979 indicated that equipment failures alone totaled about seven per day; such failures resulted in train off-loads, unscheduled train removals, or schedule delays over 10 min (*9*,p.IV–13). In addition, BARTD had significant financial problems in its first few years of operation, because revenues were unable to cover operating costs as expected (*6*,pp.24ff). Many observers believe the first general manager of BARTD had difficulty admitting publicly the scope of technical and financial problems within the system. As a result, the public (and the media) tended to control the investigation of these problems, rather than BARTD [(*1*,p.164); and e.g., see Legislative Analyst, State of California (*6*)]. Although there were substantial changes in management policies within 2 to 3 years after the system opened, the gradual improvement in public attitudes about BART are because of the considerable patience of the public during that time (*13*,pp.37–38).

Recommendation

As much as is politically feasible, problems with AHS development and implementation should be addressed candidly, both internally within the organization and externally with the public.

CONCLUSIONS

Research and development efforts in the AHS field are growing steadily and will likely continue for many years to come. Hopefully, these efforts can take advantage of the history and experience of BART and of other similar experiences of new technology in transportation. As evidenced through this study, there is wealth of insight into both good and bad practice that emerges from a detailed review of these experiences. As the transportation profession looks to the future, this review can be useful for developing both technically sound and politically and publicly acceptable innovations for the transportation system.

ACKNOWLEDGMENTS

The financial support of the FHWA, through the Precursor Systems Analysis for Automated Highway Systems, is gratefully acknowledged. Dr. Steven Shladover at PATH provided oversight for this research. Other individuals also contributed valuable comments and support, including Stein Weissenberger at PATH, Loren Bonderson and Herb Hall at Delco, and Fred Mangarelli and Amy Cochran at Hughes. However, the author remains solely responsible for the content and accuracy of the material in this report.

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Publication of this paper sponsored by Committee on Intelligent Transportation Systems.