Mission-Oriented Maintenance for Military Aircraft and Implications for Public Transportation Fleet Maintenance

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ABSTRACT

Traditionally military and civilian fleet management organizations have been designed to separate the maintenance function from the operations function as much as possible. This minimizes the need for exchange of information between operations and maintenance. The limited control available through current information management resources has justified this separation. Because real time information systems have become more powerful and less expensive, different approaches to the design of fleet management organizations have become practical. A new approach, mission-oriented maintenance, looks at the entire fleet management organization as an integral system and optimizes this system toward the primary mission. To this end it redefines the interaction between operations and maintenance. It maximizes overall flexibility and develops a new set of objectives for maintenance. The result is a system that gives maintenance a clear understanding of its role within the overall mission and significantly improves fleet availability for operational purposes. The approach is applicable to the maintenance of any fleet, and it can also be used for stationary equipment operated in large numbers to accomplish one goal (e.g., power generating equipment in an electric utility). A mission-oriented maintenance program is developed for the air force of a small country. The procedures used in this development are outlined and some results are presented. An outline is also given for a mission-oriented maintenance approach to public transportation fleets.

Over the past 30 years or so significant insights have been gained into the nature of aircraft maintenance. This was brought about by a systems approach to the processes that are responsible for the safe operation of an aircraft. One of the principal findings was that any possibility of a component failure is unacceptable if the component is vital for the safety of operations and that component failure can be virtually eliminated by proper design or by monitoring the deterioration of the component. Preventive reconditioning (overhauls) or discard of a critical component based on age or operating time was found to be an unsatisfactory protection. Instead maintenance programs have been developed that call for ongoing monitoring or periodic inspection of the condition of components. Replacement or reconditioning is performed when the observed conditions demand it. Thus the practice of time-determined overhauls has now been eliminated for critical components and is only used for noncritical components when economic conditions permit.

The practice of time-determined overhauls can be viewed as a static approach in which the times between overhauls or replacement can be optimized based on failure data and other quantitative information. The current approach, by contrast, treats maintenance as a dynamic process in which continuous actions are taken to assure most economically the continued safety of the aircraft. It amounts to the conscious management of safety of operations and avoidance of any situation where it is jeopardized. In the current approach many of the monitoring tasks are performed by operating crews during preflight checks or during normal flight operations; thus, the operating crews become part of the maintenance team.

The methods by which modern aircraft maintenance programs are being developed are well documented by the Air Transport Association (1) and Nowlan and Heap (2). The latter also include an extensive literature review and bibliography. The most important features of these aircraft maintenance programs are described in the following paragraphs.

The aircraft is divided into significant components. An analysis is performed to determine how critical each component is to the safety and completion of the mission and the characteristics of its systematic deterioration during use. Systematic deterioration may be inherent wear (fatigue or friction); or it may be caused by environmental conditions, either lasting in nature (e.g., corrosion) or instantaneous (e.g., accidents). If the rate of deterioration of a component can reasonably be reduced by lubrication, adjustment, and so forth, that activity is included in the maintenance program.

For each component critical to safety, an inspection type and inspection interval are selected that permit the identification of a deteriorating condition before it causes the component to fail. If there are alternatives, the selection is made on the basis of economic considerations and on how the maintenance task can be fitted into the usage pattern of the aircraft. If no suitable inspection can be identified, other measures are mandated. These measures may be the redesign of the component or the aircraft either to permit a suitable inspection or to make the component noncritical. In some instances, a change in the operating procedures, including changes in operating limits, may also be indicated.

For components that are not critical to safety, inspections are prescribed to prevent negative effects on, or in conjunction with, other components. If the condition of a component cannot be determined and its deterioration is related to use or age, then a periodic discard or reconditioning may be prescribed if economically justified. For components that are known to deteriorate, remedial actions are specified that have to be performed when certain levels of deterioration are detected. For other components, such as structural components that are not expected to deteriorate, remedial actions are only developed if and when deterioration is actually detected.

After all components are reviewed, the maintenance actions are assembled into a comprehensive maintenance program for the aircraft. Such a program identifies a hierarchy of checks and defines times before which these checks have to be performed. Before the maintenance program for civilian aircraft can be implemented in the United States, it has to be approved by a supervisory agency such as the Federal Aviation Administration. Once approved, the maintenance program becomes mandatory and deviations require special permission.

MAINTENANCE AND OPERATIONS

With few exceptions, airlines exist to satisfy some demand for transportation. Similarly a military fleet of aircraft exists to perform sorties to meet the requirements of the military situation. The role of maintenance is to keep aircraft in a safe and operational condition, ready to perform the missions demanded of them. Maintenance also has to have the capability to meet unforeseen circumstances that demand deviation from the prescribed course of events and to do this with a minimal disturbance of operations at a minimal cost.

The following elements can be used to minimize the cost of maintenance:

- Define the maintenance program.
- Develop an adequate set of repair procedures.
- Establish resource levels and deployment patterns for personnel, material, equipment, and standby aircraft.
- Schedule maintenance tasks.
- Schedule personnel.
- Define and establish a capability for information processing and analysis and record keeping.

To have an economically viable capability to handle unforeseen events, the maintenance function has to be as flexible as is practical. This requires a general appreciation of the need for flexibility by all maintenance personnel and one or more of the following capabilities:

- Redeployment of resources on short notice,
- Ability to defer or alter scheduled work, and
- Fast information processing and decision making.

An example of an unforeseen event is damage to an aircraft, caused either by an accident or by some unforeseen deterioration, that may require considerable work capacity to repair or that may remove the aircraft from the operational fleet for some time. Another example is disturbance in the operational pattern that might change the utilization rate of individual aircraft or that might cause aircraft not to be available for scheduled maintenance tasks. To minimize the effect of either of these events on flight operations, maintenance can keep spare aircraft and extra manpower. However, both of these measures are expensive and the need for them can be greatly reduced by structuring maintenance work and the maintenance organization in a flexible manner.

The operations department of an airline is charged with developing the best program of scheduled and charter flights that permits the most profitable use of the aircraft and with executing this program as closely as possible to the plan. In a military context the situation is not much different except that the demand often arises from a threat and is identifiable only a short time in advance.

Maintenance requirements limit the ability of operations to meet the demand and to respond to unforeseen events or disturbances. Operations has to know and understand the limitations that maintenance imposes on the use of aircraft to be able to develop the best possible operational plan. In the same way, of course, maintenance has to understand the demands from operations to be able to develop a maintenance program that best meets the operational requirements.

Traditionally maintenance and operations departments have communicated their needs to each other in the form of constraints and negotiated a mutually acceptable set of provisions. Essentially time periods are set aside during which specified numbers of aircraft have to be available for maintenance. Both maintenance and operations develop their best plans around these constraints. Any desirable deviations are negotiated in developing the airline schedule and evaluation process. In a military organization a fixed number of aircraft are often set aside for maintenance, and the military command does not plan on their availability. Of course, in a battle situation the commander may decide to use the maintenance aircraft for operations as well.

Undoubtedly the existence of constraints, which separate the spheres of maintenance and operations from each other, can simplify the management problem. Each department manages its affairs as independently as possible. However, this independence has its price and it is believed that if the boundaries between operations and maintenance could be relaxed, the organization would be able to meet the demand more economically. Modern means of communication and information processing should make it possible to increase the flexibility between operations and maintenance; however, developing a mission-oriented maintenance system is a technical prerequisite. Organizational changes are also necessary to realize the benefits fully.

MISSION-ORIENTED MAINTENANCE

The Air Transport Association has specified a set of maintenance tasks for each component. Tasks were selected on the basis of economic analysis and how well they would fit into the work flow of maintenance shops and operational patterns. However, maintenance frequently has to be performed under circumstances that are quite different from the planned conditions. The constellation of parameters assumed in the economic analysis does not apply in these situations. The use of resources that were previously acquired, possibly at great expense, may make little or no difference in total cost. Other resources that could have previously been acquired at little cost, but were not, may not be available at any price on short notice. In addition, alternative courses of action, such as standby aircraft or schedule changes, are not possible without a long lead time.

It follows, therefore, that it would be more desirable to select the optimal maintenance task when the actual situation under which the task has to be performed is known. Of course, an economic optimization cannot be undertaken every time maintenance is required. Instead, a well structured program can be developed, which offers specific choices and precise instructions on how to make the selection.

The situation is similar at the level of checks. Individual tasks are packaged into checks based mostly on ease of administration and, to some degree, economics. Maintenance tasks are neatly packaged into checks so that total maintenance progress is easier to track and work is easier to schedule. If, for unforeseen reasons, the workload on a given day is excessive, it would be advantageous to perform only the work that is absolutely necessary instead of the whole package. The deferred items can be handled whenever capacity becomes available again or whenever their time limit expires. As with individual maintenance tasks, such a system would become unmanageable unless a system were introduced and a capability for information processing were available.

Making a maintenance program more flexible means that the aircraft can be used more effectively for the mission of the organization. A flexible maintenance program is commonly referred to as mission-oriented maintenance. Mission-oriented maintenance does not minimize maintenance cost or aircraft downtime nor can it be used to defer maintenance indefinitely. The temptation to do so, however, clearly exists. Therefore, a mission-oriented maintenance program can only be implemented if genuine cooperation exists between maintenance and operations. This cooperation requires an effective and reliable means of communication.

Many elements of a mission-oriented maintenance program are standard in many airlines today, although none is known to have a formal program in place. In the following section mission-oriented maintenance programs for a military organization are briefly described. Then an outline is given for the development of a mission-oriented maintenance program for an airline or other civilian operators of fleets of vehicles in scheduled transportation.

MISSION-ORIENTED MAINTENANCE PROGRAMS FOR A MILITARY ORGANIZATION

The mission-oriented maintenance programs described here were developed within the context of a project to restructure the maintenance and logistics section of the air force of a small, nonaligned country. The project included the development of new organizational structures and procedures for operations, planning, decision making, and information processing. The project was motivated by the expected acquisition of the latest technology combat aircraft.

The military objective is strictly limited to territorial defense. It is expected that almost any hostile engagement will take place within the boundaries of the country. Because the country is small it is expected that when a hostile engagement starts, no part of the country may be assumed to be safe. Consequently it is not possible to plan a staging area, and all personnel, material, equipment, and facilities are expected to be affected by combat.

Without going into details, a wartime scenario may be characterized by a prolonged period of tension, interrupted by episodes of combat. The duration of each combat episode is expected to be on the order of several days. During these episodes, flying activity will be at a high level and all aircraft will be on alert. During the intervening periods of tension flying activity will be less but the requirements for readiness will still be high. During wartime all aircraft will be operated in small groups from makeshift bases scattered throughout the country. In times of combat it is expected that frequent relocations will occur.

The point of departure for the development of the mission-oriented maintenance programs was conventional maintenance programs based on manufacturers' recommendations and approved by an independent authority. This authority operates much as the Federal Aviation Administration does in the United States for civilian aircraft. All maintenance programs that were in effect at the beginning of the project had been in place for years; therefore, the military organizations and the work force were accustomed to them. It was widely recognized, however, that aircraft ground times were excessive.

The first step in developing the mission-oriented maintenance programs was to assemble a comprehensive data base encompassing the following information:

- Existing maintenance programs,
- Existing maintenance practices,
- Wartime mission scenarios for aircraft and maintenance personnel,
- Estimates of qualitative and quantitative requirements for damage repair during periods of military conflict, and
- Maintenance requirements of aircraft components.

In addition to permitting a more systematic development of the new maintenance programs, the data base was intended to provide

- A basis for comparing the effectiveness of the existing maintenance programs with that of the new programs.
- An assurance that the existing programs and practices would be used as a basis for the new programs. Much thought that had gone into developing the existing practices could be transferred to developing the new programs and practices. Thorough analysis of the existing situation could help assure that the new programs and practices called for a minimum amount of change and disruption.
- An educational experience for the members of the project team, most of whom had little experience in designing a maintenance program. Analysis of the current situation sharpened their perception and awareness of factors that determine the effectiveness of a maintenance program design.
- Some immediate improvements in the practice of maintenance.

Objectives for the Wartime Maintenance Programs

After the data base had been assembled, it was possible to state what form maintenance programs for wartime could take and what objectives could be met. A wartime maintenance program is the best expression of what is possible. Holding off the specification of objectives for the wartime maintenance programs until completion of the basic information made it possible to make the objectives realistic.

The most important objectives are described briefly below.

1. Safety must be assured at all times. It is tempting to think that during combat safety will be of little importance. Certainly many situations will occur when adherence to restrictions imposed by safety considerations will probably mean death. However, the purpose is to limit these situations to unforeseeable events and to assure safety in all other cases.

2. It has to be possible to sustain wartime operations indefinitely according to the given operations profiles. This means keeping up with all maintenance work and expected repairs in the mode of operation planned for wartime.

3. The sum total of resources required for peace and wartime operations of the maintenance program has to be minimized. This is different from minimizing peacetime and wartime maintenance programs separately. It is also different from minimizing the

manpower or equipment required for some particular maintenance task. Minimizing the sum total of resources required implies that there is no penalty for using resources that are already available. Thus minimizing workload is only important when it would exceed the capacity of available personnel. Minimization of aircraft downtime is not important as long as it does not interfere with the requirements of the military command (i.e., as long as it can be accommodated in the operational windows made available by the military command). In fact a general principle has been adapted to aircraft maintenance: All resources, once acquired, are free unless they can be gainfully disposed of.

4. During wartime all aircraft have to be operational or at least be operational within a short time specified by the military command.

5. The transition from peacetime operations to wartime operations has to be accomplished within a short time.

The objectives just stated imply that all maintenance work has to be arranged in small packages, each one of which can be done in a few hours. Furthermore, from any point within any package, it should be possible to reach a flyable condition within a short period of time. No absolute limits were specified for either of these times; instead the personnel developing the maintenance programs were instructed to make them as small as reasonably practical. The requirement for quick transition from peacetime to wartime maintenance means that the wartime maintenance programs must be essentially part of the peacetime maintenance programs.

New Maintenance Programs

The new maintenance programs are based on a definition of states of maintenance of an aircraft. The following states were defined.

I--Aircraft meets all peacetime maintenance requirements.

II--Aircraft meets all wartime maintenance requirements but violates some peacetime requirements.

III--Aircraft has exceeded the due date for a maintenance event. To define this state completely it is necessary to know which maintenance event is past due and which parts of the work included in that maintenance event have already been completed.

IV--A component has exceeded a time limit.

V--Aircraft is not airworthy.

Figure 1 shows a typical profile along which an aircraft might progress from peacetime through wartime. Naturally the aircraft starts out in state I (i.e., it meets all peacetime requirements). The target state for wartime is state II, when all wartime maintenance requirements are met. The time the aircraft spends in state II is interrupted by times in states III and IV, when due dates for aircraft or component maintenance work have been exceeded. During these times special inspections may have to be performed. The flying hours spent in these two states at any one time are limited. If they are exceeded, the aircraft enters state V. Because this event should not occur if the programs are followed, it is not shown in the diagram.

The new maintenance programs were developed by proceeding through the following steps:

1. Assume a time by which the due date for each aircraft maintenance event can be exceeded.

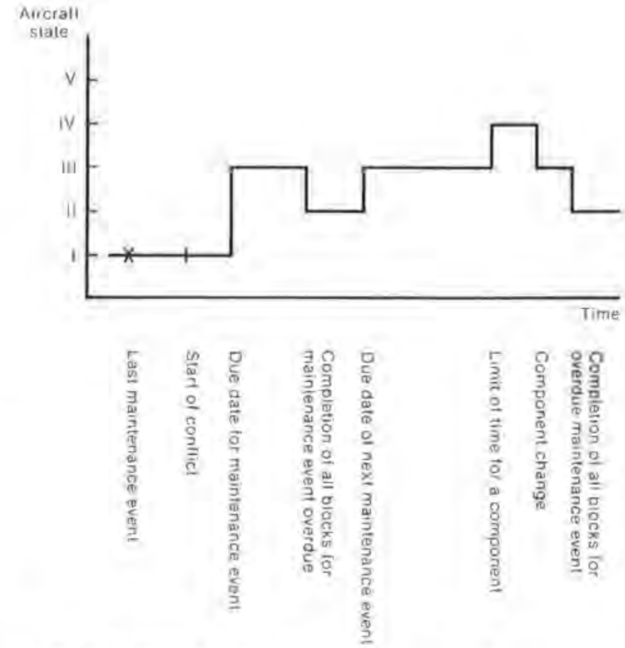

FIGURE 1 Typical profile of states for an aircraft.

2. Analyze each task in the maintenance event by asking the following two questions:
   - How can this task be simplified in peacetime as well as in wartime?
   - Which inspections will have to be performed during the time this maintenance task is past due (state III)? Specify the type and frequency of inspection.

Most of this information was collected in the analysis of the maintenance requirements of components. This step therefore consists mostly of gathering and reviewing this past information.

3. Analyze all time-limited, individually tracked components and for each one of these components
   - Determine by how much the time limit can be exceeded (the length of time the component may remain in state IV) and
   - Determine which, if any, inspections will have to be performed during state IV.

Again this step consists mostly of collecting information previously developed.

4. Arrange all maintenance events into packages that can meaningfully be done together and that meet the specified objectives. Draw network diagrams, if necessary.

5. Arrange all the packages developed above for each check, together with the additional tasks included in the peacetime maintenance program, in a project network and find the optimal duration for the check.

Results

Mission-oriented maintenance programs were developed for all helicopter fleets and combat aircraft. Wartime versions were developed for all but the highest level check, the airframe overhaul. It was determined that the airframe overhaul could be postponed safely for any realistically anticipated duration of a war.

The results by far exceeded the most optimistic expectations. The wartime maintenance programs easily met all of the objectives. The time limits on states III and IV were considerably longer than expected. A surprising number of tasks from the original programs were found to serve no purpose and could be eliminated for the new peacetime maintenance programs. For the new wartime programs a large number of additional tasks could be eliminated. Tables 1 and 2 give the results for the wartime program for one of the helicopters. The time limit for state III from all levels of checks was 200 flight hours. As can be seen, the additional inspections that have to be performed during state III are minimal and can be easily accommodated in the anticipated mission scenarios.

TABLE 1 Results for a Helicopter, States I and II

Maintenance Event	Number of Tasks	
	State I	State II
100 hr	106	43
300 hr	123	54
1,200 hr	121	31

TABLE 2 Results for a Helicopter, State III

State III Inspections					
As Necessary		Daily		Every 25 hr	
Number	Time (min)	Number	Time (min)	Number	Time (min)
4	180	3	15	2	15
5	210	5	25	3	25
1	30	5	45	10	205

The wartime maintenance programs were tested during maneuvers. The results of these confirmed that it is possible to perform all maintenance tasks under battlefield conditions and within time windows specified by the military command. No aircraft scheduled for operations was unavailable because of maintenance. Also, it was possible to keep up with all maintenance work that became due, so there was no backlog of deferred maintenance work at the end of maneuvers.

The backlog of maintenance work is difficult to measure. In this case the measure was the total number of hours that could be flown before different levels of checks would become due on all aircraft. This number actually decreased during the maneuvers for all checks except the highest one. Another measure was the discounted expected future work load (DEFL). This measure calculates all expected future work discounted to the present over the hours that can be flown before the work is due. It compresses into one number all information about the future work. An increase in this number indicates an increase in the backlog. For a description of this measure refer to Etschmaier (3). The DEFL calculated over the duration of the maneuvers for the fighter aircraft increased slightly. The reason, however, was that progress made on overhauls during that period was not included in the calculation.

When the work packages of the wartime maintenance programs, together with the additional peacetime tasks, were assembled into peacetime checks, significant reductions in ground time compared with the old peacetime checks were realized. For example, for the fighter aircraft the total amount of ground time over all checks, including the airframe overhaul, was reduced by 46 percent. This resulted in several additional aircraft being made available to operations. Essentially the operational fleet was increased without any capital expenditure, because the additional expenses consisted of the cost of the development work and the investment in spare parts, tools, and equipment. This was negligible compared to the capital value of the added operational aircraft.

MISSION-ORIENTED MAINTENANCE FOR PUBLIC TRANSPORTATION FLEETS

Compared with the military situation, public transportation fleets may be regarded as being in a continuous state of war. There is no equivalent of a peacetime that allows preparation and practice. Instead, the fleet is always engaged in the performance of its primary missions. Therefore it is not meaningful to make a distinction between equivalent peacetime and wartime maintenance programs. However, few fleets can be considered as being in the same state all the time. There are peak periods when most vehicles are needed, off-peak periods when only some of them are needed, and periods when all vehicles are idle. Apart from times of normal operations there are also times when special needs for vehicles arise, for example, charter or emergency services. Another example would be times when the operational pattern is disturbed and more vehicles are needed to satisfy the normal demand (inclement weather is a frequent cause). Finally technical problems may arise that may reduce either the available fleet or the manpower available to perform the normal maintenance program. In all of these cases maintenance programs with a mission orientation can be of considerable benefit.

The most important aspect of a mission-oriented maintenance program is that it could provide flexibility to cope with each one of these situations. It could provide flexibility in the work to be performed as well as in when to perform the work. As in the military situation described, it could provide alternative ways of assuring the same level of safety. For example, some deterioration can be detected before it becomes critical either by a rather superficial, simple inspection or by a thorough one requiring considerable downtime and possibly special tools and equipment.

The superficial inspection will provide a relatively short warning time (i.e., the time from when the deterioration is first recognizable until it becomes critical). This inspection has to be performed rather frequently. On the other hand, the thorough inspection would provide a long warning time and thus would be performed infrequently. In the long run, the total time in man-hours as well as in vehicle downtime required for the simple inspection may exceed that required for the thorough inspection. However, if the simple inspection can be accommodated in operational windows and the more thorough one cannot, the simple inspection might still be preferable.

What is preferable might depend on the specific situation at a given time, and the situation may change from time to time. It would be beneficial if the maintenance program would allow for either method. The same is true for breaking larger maintenance checks into smaller packages that would be performed one at a time.

Although a mission-oriented maintenance program can provide considerable benefits to most fleets of public transportation, it would be naive to expect that such a program could be implemented without supporting action. Considerable changes in organizational structure and mode of operation would be necessary in most cases. Even though changes would not be expensive, they would require the understanding and cooperation of the entire organization to be permanently successful. The changes would affect the way operational decisions are made and how information is processed and transmitted within the organization.

A considerable information processing capability would be necessary to monitor the maintenance status of each vehicle at any time and to identify those vehicles that are nearing some limit. Also, it is necessary to have measures that indicate the status of the maintenance workload for the entire fleet. In the current system it can be detected quickly whether the maintenance workload is being kept up, especially for the lower level checks. If flexibility were introduced, it would be possible to accumulate a large backlog of work that would have to be performed at the same time. It might not be obvious, however, particularly if the maintenance department were occupied with some problem that required urgent attention. The measure of the discounted expected future workload (DEFL) was developed to protect against uncontrolled increase of the work backlog. By choosing the proper discount rate, different DEFLs could be used to highlight long-range and short-range problems.

The task of scheduling work, given the increased flexibility, would be much easier with a mission-oriented maintenance program. There might be many more tasks to keep track of, however, and a much more complicated description of the maintenance status of each vehicle. This may well be beyond the capabilities of most conventional scheduling practices, either manual or computerized. Innovative methods of scheduling would have to be developed that would be capable of handling a large amount of information for a problem with many equally good solutions. For more details on possible solutions see Etschmaier (3,4).

Airlines

Airlines occupy a special place among operators of public transportation fleets because their vehicles are the most expensive, the most technologically advanced, and the most vulnerable. Also, the airline industry is the youngest of all transportation industries. For all these reasons, airlines have the most advanced maintenance programs. Most maintenance work for airlines is done when the aircraft are not needed for operations. For short haul operations this is usually during the night. Standby ratios of 1 or 2 percent are quite common.

The practice of systematically establishing minimum equipment lists (i.e., lists of equipment that has to operate if the aircraft is to be used in flight service) provides considerable flexibility for using aircraft with defects in components not on the list. Or, viewed another way, it provides flexibility in when repairs of defective components have to be performed. The trend in engine maintenance points in the same direction. More and more engines are removed from aircraft not because they are malfunctioning but because their rate of fuel consumption exceeds some limits. In the absence of safety considerations, considerable flexibility exists as to when to remove an engine.

There can be little doubt that the maintenance programs in effect at most airlines are at least near optimal for systems where all aircraft of a fleet, or possibly a subfleet, are used in the same way. This is the way most airlines plan to operate; however, there may be air services that do not fit this pattern. Examples are isolated routes, charter service, and networks with pronounced radial structures, where all aircraft fly from one point on the periphery through the central hub to another point on the periphery. In this time of deregulation it would be desirable to experiment with many different service alternatives. For such experiments existing maintenance programs could prove to be less than optimal.

In summary, it appears that although airlines already have excellent maintenance programs, benefits could still be gained by incorporating a mission-oriented program. For fleets that have not shared the recent developments in airline maintenance the potential benefits are much more significant.

Urban Bus Transit

Urban bus transit is an example of public transportation that is probably at the other end of the spectrum from airlines when it comes to maintenance. Transit bus maintenance has not progressed in the same way as that for airlines. In transit many people still believe that the best maintenance policy is preventive rework or discard of components on the basis of age. They expect that if life limits are properly chosen, in-service failures can be eliminated and the entire operation will be optimal. Others are looking for technological improvements that are expected to help accomplish this.

A recent study by Etschmaier (5) put these efforts into perspective. The study also showed that the record of transit bus maintenance is not good. Indications are that although the money spent has increased considerably, performance has not improved. The study advocates a completely new look at all aspects of maintenance in a transit system. Within such an effort, mission-oriented maintenance programs could be developed in a way similar to that described in the military project. Significant improvements can be expected, and there would be no need for big investments or for additional manpower. It must be recognized, however, that mission orientation requires a new look at the entire system. Without this, improvements are not likely to occur.

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A Model for Determining the Width of Airport Pedestrian Corridors

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ABSTRACT

A mathematical model for designing pedestrian corridors in airport terminals is presented. The model is based on a concept of minimizing the sum of construction costs, operating costs, and passenger walking time. The development of the model is explained. The model has been written for use with a hand-held programmable calculator and tested to check the validity of the model results against other design procedures. A sensitivity analysis was performed to determine the effects of different values for independent variables. Finally, the model results are compared with an actual terminal building design. The design procedure selected a width very close to the actual design. The results indicate that the model may be a useful tool in selecting the width of passenger corridors.

Many models have been developed for designing airport passenger terminals. Service facilities such as ticket counters, security checkpoints, and gate check-in lend themselves to modeling as queuing processes. The overall design philosophy has been modeled by both de Neufville (1) and Braaksma (2). The size of waiting areas at boarding gates is based on queue size for passengers arriving at the gate (3). The size of walking areas is based primarily on the work of Fruin (4). Design is based on the desired level of service and the facility size is chosen to meet that level of service for the pedestrian flow. This concept is illustrated in Figure 1.

The levels of service normally associated with terminal design are B and C. At level B the pedestrian is free to select a walking speed, but may experience crossing and reverse direction conflicts. This level would be an appropriate design for terminals without severe peaking. At level C the pedestrian's freedom of speed becomes restricted and is appropriate for terminals that have severe peaking.

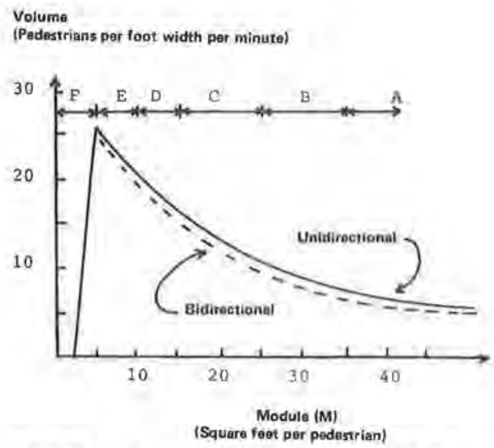

FIGURE 1 Volume of pedestrian flow and area occupied on walkways *(4)*.

Levels of service D, E, and F are not considered to be appropriate for design, although D and E might be acceptable during very short peak flow periods.

As can be seen, this design procedure relies heavily on the judgment of the designer for determining an appropriate level of service and then selecting a point within the range of the level of service. No specific consideration is given to the trade-off between costs of congestion and costs to construct, operate, and maintain wider corridors. de Neufville and Grillot (5) note that the selection of level of service represents a compromise between construction costs and inconvenience. Economic efficiency requires that a system operate at the point of minimum cost. In this case that point is the minimum of the sum of delay, construction, and operating costs. A rational design procedure would be to minimize some function of costs. This model formulation develops such a design procedure.

MODEL FORMULATION

To minimize the sum of pedestrian delay, construc-