Simulation Study To Evaluate Spare Ratios in Bus Transit Systems

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A simulation model was developed to investigate proper choice of the spare ratio to maintain a desirable level of service dependability. The objective of the model was to study the effects of the time between bus breakdowns and the time to repair broken buses, as well as other characteristics of the system, on the value of the spare ratio and the overall performance of the transit system. The model was successfully validated and used to simulate and study the bus operations of an existing transit system. The model can be adapted to simulate the operations of different bus transit systems.

The overall reliability of the service provided by a bus transit system is a function of a number of factors, including mechanical reliability of buses, availability of spares to replace broken buses, and total time elapsed until disabled buses are fixed and sent back to operation.

The main objective of the research described in this paper was to investigate the proper number of spare buses needed to maintain a desirable level of service reliability. The investigation includes a study of the effects of bus mechanical reliability, time to repair failed buses, and repair schedule policies on the spare ratio level. The spare ratio is defined as the ratio of the number of spare buses in the fleet to the maximum number of buses scheduled at peak periods. A simulation model was developed to examine

- The relationship between frequency of bus breakdowns and the spare ratio and its effect on the level of service;
- The relationship between the number of mechanics working at the repair garage (or repair turnaround) and the spare ratio;
- The relationship between the frequency of breakdowns of individual bus components and the spare ratio; and
- The relationship between scheduling policies practiced at the repair shop and the spare ratio level required.

A bus transit system with a fleet of 57 buses was selected from a hilly, medium-sized city in the Mid-Atlantic region as the basis for the simulation model. The model can also be used to simulate the operation of other transit systems if some of the input parameters and parts of the model are changed.

LITERATURE REVIEW

Although a great deal has been written about issues related to bus maintenance, no literature has specifically addressed the spare ratio. Several researchers have studied bus systems and developed models to predict or enhance performance indicators. These indicators have usually been linked to operating costs (*1, 2*), preventive maintenance policies (*3*), resource use (*4*), repair scheduling (*1*), bus scheduling and bus boarding time (*5*), passenger waiting and traveling time (*6*), transit system reliability (*7*), and other issues, all either directly or indirectly related to the spare ratio problem. In general, research reported in the literature can be classified into one of five areas:

- *Data collection and preparation.* In this area, Maze et al. (*8*) provided methods to obtain information on maintenance planning and fleet management. Maze and Dutta (*9*) illustrated a statistically based method to quantify and compare life characteristics of bus components in an operational setting. Kosinski et al. (*10*) also provided methods to generate statistics on bus component failures.
- *Application of universal methodologies and guidelines.* In 1981, UMTA attempted to develop standard maintenance guidelines to be used by transit systems (*11*) but had to abandon its effort for lack of agreement on universally accepted standards. Tradeoffs between capital costs, operating expenses, and maintenance work were addressed by Dutta et al. (*1*) and Wilson (*2*), but no guidelines were developed because of the unique characteristics of the individual transit systems.
- *Analysis of relationships between resources and system performance.* Maze et al. (*12*) developed a simulation model of a hypothetical maintenance system to examine different policies in maintenance planning. Maze et al. (*13*) and Sinha and Bhandri (*3*) developed simulation models to investigate relationships between system performance and availability of resources.
- *Analysis of relationships between environmental conditions and system performance.* Effects of terrain, climate, fleet age, and other factors on maintenance manpower requirements were investigated by Wilson (*2*) and Drake and Carter (*4*).
- *Impact of maintenance policies on system performance.* Sinha and Bhandri (*3*) investigated the relationship between preventive maintenance policies and system performance. Guenthner and Sinha (*7*) studied the impact of maintenance strategies on service reliability. Dutta et al. (*1*), and Martin-Vega (*14*) also investigated the impact of repair scheduling policy on the performance of bus transit systems.

MODEL INPUT

Information collected from the transit system under consideration consisted primarily of bus breakdown records and

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TABLE 1 BUS SCHEDULE

		No. Scheduled on Weekdays (Saturdays)				
		Morning			Evening	
Group	Total No. of Buses	Off-Peak	Peak	Mid-Day (Off-Peak)	Peak	Off-Peak
1. Bluebird	10	2(6)	6(6)	2(6)	6(6)	2(6)
2. National	5	2(2)	4(2)	2(2)	4(2)	2(2)
3. AM General	7	0(0)	0(0)	0(0)	0(0)	0(0)
4. GMC	23	15(15)	22(15)	15(15)	22(15)	15(15)
5. Flxible	12	10(11)	12(11)	10(11)	12(11)	10(11)
Total	57	29(34)	44(34)	29(34)	44(34)	29(34)

repair data for system operation during fiscal year 1986–1987. This information was used to produce summaries and statistical distributions for the number of miles between breakdowns and repair times for the individual components of different bus groups used in the system. Data were collected for only a single year, but they cover several types of buses with varying ages.

In generating breakdowns in the simulation model, it was assumed that failure patterns vary between types of buses but are the same for buses of the same type and age. The buses were therefore categorized into five groups according to their type and age. The number of buses in each group is given in Table 1.

Data files were maintained for work performed on more than 200 individual components. To simplify the simulation input, these components were grouped into the following 19 categories, each containing several components:

- Scheduled state inspections;
- 3,000- and 9,000-mi inspections;
- 6,000-mi inspections;
- 12,000-mi inspections;
- Axles;
- Braking system;
- Cooling system;
- Drive line;
- Electrical system;
- Fuel system;
- Fare box;
- Heating system;
- Air conditioning system;
- Body, seats, doors, and windows;
- Engine;
- Steering system;
- Suspension system;
- Transmission system; and
- Other repairs and maintenance.

A team of 12 mechanics was scheduled for work during the morning shift (7:00 a.m.–3:00 p.m.), and teams of 5 mechanics were scheduled for the other shifts (3:00–11:00 p.m. and 11:00 p.m.–7:00 a.m.), 6 days each week, Monday through Saturday. During the second and third shifts, minor jobs such as cleaning, washing, checking fuel, repairing lights, fixing flat tires, and mending radio equipment were performed.

Buses are scheduled for operation between 4:35 a.m. and 12:55 a.m., weekdays and Saturdays, according to the schedule presented in Table 1. On Sundays, five buses from Group 5 are scheduled to operate for 2 hours only. The spare ratio for this system can thus be calculated as 13/44, or 29.5 percent.

DATA PREPARATION

A data base was created with 6,466 records, one for each inspection or repair job completed. This data base was used to generate distributions for time between failures and repair times.

Distributions of Time Between Failures

Each of the five bus groups was considered a separate entity in the simulation model. This approach was easier and more practical than considering each bus alone. Buses of the same group were assumed to be similar in all aspects and to possess the same characteristics, including failure patterns.

All records were classified into five files, corresponding to the bus groups. Each of these files was then broken down into 19 different smaller groups, corresponding to the 19 categories of bus components. Thus $5 \times 19 = 95$ different groups were obtained and used to generate time between failures for each component category within a bus group.

The repair data contained the date of the repair, which was assumed to be close enough to the breakdown date. The bus mileage at the time of breakdown, however, was not recorded. Because the number of buses on the road was not constant at different times and dates, it was necessary to convert the time between breakdowns into mileage between breakdowns. The number of inspections performed at 3,000-mi intervals was determined and used to calculate the total mileage per bus group per year and the average mileage that each bus was driven per day. For each bus group, the average speed was estimated as the ratio of total miles to total number of hours on the road per year.

The average mileage per day for each group of buses and the number of days between breakdowns were used to obtain frequency distributions for miles between breakdowns for all component categories within each bus group. These distributions were then used to generate breakdowns in one of three ways:

- *Exponential distribution.* Data for the group were successfully tested to fit the distribution. The χ^2 goodness-of-fit test was used for this purpose.
- *Cumulative probabilities (empirical distributions).* If no standard statistical distribution could fit the data, this method was used directly to generate miles between breakdowns.
- *Generation of breakdowns.* If few observations were available (e.g., two or three breakdowns), the exact numbers of breakdowns were generated at equal intervals during the year. This method was also used for inspections.

Repair Time Distributions

To generate repair times, individual bus components were grouped into the 19 categories identified earlier. Unlike failure rates, repair times were not assumed to depend on the bus group. The 6,466 records for repair times were thus placed into only 19 data groups. The Shapiro-Wilk and Kolmogorov-Smirnov nonparametric tests were used to test whether the repair times for each category followed a normal distribution.

The units used for the repair time were small enough that the data could be considered continuous. It developed that none of the groups followed a normal distribution. Grouping the data into a larger number of more homogeneous categories could lead to better normal fits, but this procedure would add to the complexity of the model. Because no other probability distribution could be identified to fit the data closely, cumulative probabilities were used directly to generate repair times.

SIMULATION MODEL DEVELOPMENT

An investigation was made of the effects of the following parameters on the desired level of the bus spare ratio:

- Number of mechanics on duty,
- Time between bus breakdowns, and
- Policies practiced in the repair shop.

The simulation model was designed to provide the following information under various operating conditions:

- Usage of mechanics,
- Average waiting time for repair,
- Average time spent in the repair system, and
- Percentage of time that the system is faced with a bus shortage and cannot fully meet the schedule.

To represent the transit system and its maintenance facilities as closely to reality as possible, all buses were classified into one of the following categories:

- *Active buses.* Operative and regularly scheduled for service;
- *Spare buses.* Operative but not regularly scheduled; and
- *Failed buses.* Inoperative because of mechanical failure, preventive maintenance, or inspection.

This method of classification is not standard practice; however, it was the method used by the system under consideration.

Assumptions of the Model

Various assumptions were made and maintained throughout the simulation. Failures were classified into critical and noncritical categories, in which critical failures are those that cause interruption of service and put the bus out of commission until it is fixed. Noncritical breakdowns do not interrupt the bus service but require repair work at the end of the scheduled operation of the bus. The ratio of critical to noncritical failures can be changed as a parameter in the simulation model, depending on the characteristics of the system under consideration.

When a critical failure occurs, a mechanic takes a spare bus, if available, to the location of failure. The spare bus replaces the failed one, and the mechanic either fixes the failed bus on location or tows it back to the garage, where it is scheduled for repair according to the priority set at the shop. The following order is followed when substituting a failed bus with a spare, depending on the availability:

1. Replace the failed bus with a bus from the same group.
2. Replace the failed bus with a bus from Group 3, which consisted of buses designated as spares.
3. Replace the failed bus with a bus from another group that has the same capacity.

The same order is followed when buses are scheduled for operation.

The percentage of times that a mechanic can repair a failed bus on location can be changed as a parameter in the model. It is also assumed that maintenance workers are interchangeable and can perform all repairs.

The model assumes that repair times and miles between breakdowns are stochastic in nature, but inspections are performed at fixed intervals. Maintenance equipment, tools, and replacement parts are assumed to be always available. Travel time to location of a failed bus and back to the shop is uniformly distributed between 10 and 20 min, and towing time is uniformly distributed between 20 and 40 minutes.

In general, noncritical breakdowns need smaller repair times than the critical ones. Inspections are treated as noncritical failures.

Elements of the Model

An overall flowchart of the simulation model is given in Figure 1. The model consists of five elements.

Breakdown Generation

Five entities representing the five groups of buses were considered to be subject to periodic failures. Each entity has its own attributes that define its status and characteristics. Miles between breakdowns were generated separately for each component category within each bus group according to its predetermined probability distribution.

As the simulation progresses, mileages are accumulated for each bus group according to the number of active buses on the road for that group and their average speed. The number of buses on the road changes with time and depends on both operation schedule and bus availability. The time of the next failure was therefore not easy to predict because it was constantly changing with the number of buses on the road for the group.

Scheduled Changes in the Number of Buses

The number of buses scheduled for operation changes several times during each day, Monday through Friday. Different schedules are also planned for Saturdays and Sundays. To simplify the bus operation schedule in the simulation, a complete cycle with 39 periods was developed for the entire week and repeated throughout the simulation. Whenever the num-

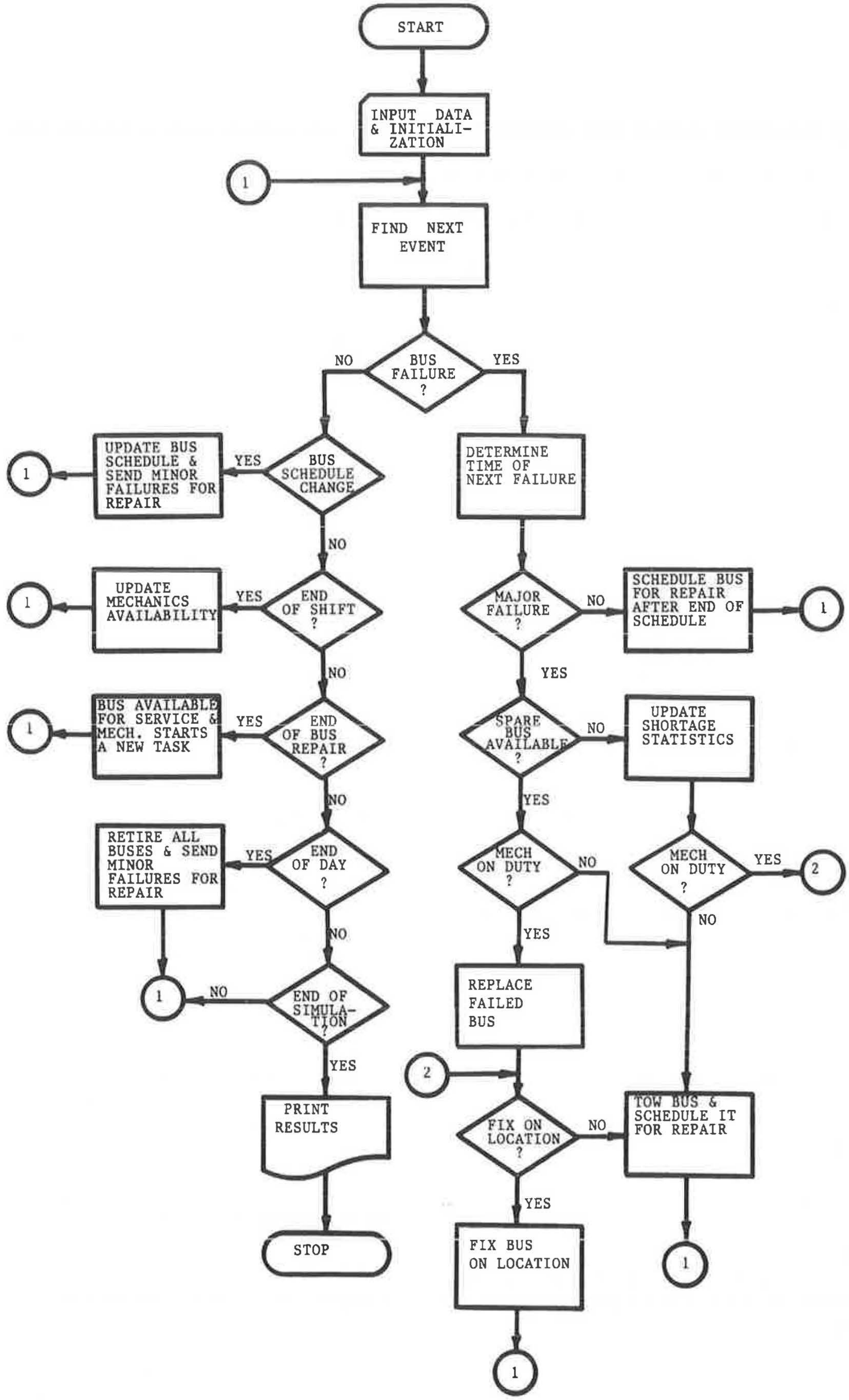

FIGURE 1 **Flowchart of the simulation model.**

ber of buses in operation was reduced, during the change from a peak period to an off-peak period or at the end of the day, buses with noncritical breakdowns were pulled first and scheduled for repair.

Scheduled Changes in the Number of Mechanics on Duty

Different numbers of mechanics are scheduled to work during the three daily shifts, Monday through Saturday. A complete cycle of 19 shifts (three 8-hr shifts for Monday through Saturday and one 24-hr shift with no mechanic for Sunday) was used for the entire week in the simulation.

The morning shift is usually staffed with more mechanics than the other two shifts. For simplicity, it was assumed that when the mechanics change between shifts, the new crew continues the work started by the old one. If the number of mechanics between shifts increased or decreased, appropriate action, such as starting repair on a bus or interrupting repair work being performed, was taken.

End of Repair on a Bus

Two actions are taken whenever a repair job is completed. First, the freed mechanic checks for waiting buses and starts working on the first bus in the queue. If the queue is empty, the mechanic becomes idle, which in reality means performing other jobs such as fueling, cleaning, and so on. Second, the bus that was just repaired is returned to service, either as an active bus or as a spare, depending on the number of buses scheduled for service and the number of buses available.

End of the Day

The end of the day is defined as the time at which all buses return from service. At this time, all in-service buses with noncritical breakdowns are scheduled for repair.

Program Overview

The transit system operation was simulated using a FORTRAN and SLAM II simulation program (*15*). The program starts by reading all input variables, arrays, and parameters and performing the necessary initialization. Breakdowns are then scheduled for each bus group, and control of the program is transferred to SLAM II. The SLAM II program finds the next event to occur, calls the appropriate subroutine for that event, and controls the flow of events and all operations. After a warm-up period, statistics are collected on the system performance measures. By changing the parameters of the system, these statistics can be collected under different configurations and operating policies. The main parameters that were investigated are

- Spare ratio (the value of the spare ratio was controlled by changing the number of spare buses available),
- Number of mechanics,
- Repair scheduling policies, and
- Rate of breakdown for different component categories of the five bus groups.

MODEL APPLICATION AND ANALYSIS OF RESULTS

The simulation model was successfully validated against the actual operational data of the system. The number of breakdowns per bus type, number of breakdowns per component, use of mechanics, and repair times generated by the model were compared with the actual operational values, and no significant difference was found. Sensitivity analyses were performed on the input parameters and model variables, and the model responded as expected [for details of the validation process and results, refer to the report by Iskander and Jaraiedi (*16*)].

The model was then implemented under different conditions by varying its parameters and input variables. The main objective was to investigate the effects of several parameters and variables on the value of the fleet spare ratio required to maintain a desirable level of service. The following measures of performance were selected to represent the level of service rendered to the riders and the turnaround in the repair garage:

- *System dependability*. System dependability, D, was defined as

$$D = 1 - (B_M/B_T)$$

where B_M is bus-hours of missed runs and B_T is total bus-hours of operation. The higher the number of bus-hours missed due to breakdowns, the lower the dependability of the system.

- *Time in system*. TISYS is the total time (waiting plus repair) spent by a bus at the repair shop.
- *Average number of buses in the repair queue*. This measure is represented by the variable LQU (for "length of queue").

The effects of the following parameters and variables on the desired level of the spare ratio were investigated:

- Availability of resources (mechanics) at the repair shop,
- Repair scheduling policies, and
- Rates of failure of different bus components.

The rates of failure depend on several factors, such as age of component, climate, terrain, and so on. By individually adjusting the rates of failure of the bus components, the effects of different factors on the value of the spare ratio required can be investigated.

Relationships Among the Spare Ratio, Number of Mechanics, and System Performance

Because the reliability of a bus or its components is primarily measured as a function of the mileage between breakdowns under normal operating conditions, its value does not change with the spare ratio or the number of mechanics available. A higher spare ratio, however, increases the probability of having a spare bus when one is needed. Also, a higher number of mechanics usually results in faster turnaround at the repair

TABLE 2 RELATIONSHIPS AMONG SPARE RATIO, NUMBER OF MECHANICS, AND SYSTEM PERFORMANCE

	Number of Mechanics at				
Spare Ratio (%)	Evening & Night Shifts	Morning Shift	D	TISYS	LQU
	3	5	0.9266	6.09	2.05
	3	6	0.9440	5.72	1.85
11.4	3	8	0.9520	5.56	1.70
	4	5	0.9647	4.68	1.14
	4	8	0.9662	4.55	1.10
	5	5	0.9797	4.24	0.81
	3	5	0.9824	6.09	2.06
	3	6	0.9897	5.85	1.89
20.5	3	8	0.9899	5.77	1.82
	4	5	0.9964	4.89	1.22
	4	8	0.9972	4.62	1.19
	5	5	0.9979	4.28	0.85
	3	5	0.9964	6.29	2.18
	3	6	0.9965	5.80	1.93
29.5	3	8	0.9966	5.46	1.69
	4	5	0.9986	4.84	1.20
	4	8	0.9988	4.79	1.13
	5	5	1.0000	4.28	0.81
	3	5	0.9994	5.76	1.86
	3	6	1.0000	5.52	1.68
40.9	3	8	1.0000	5.37	1.60
	4	5	1.0000	4.72	1.15
	4	8	1.0000	4.55	1.07
	5	5	1.0000	4.16	0.79

shop and improves the availability of buses. An increase in the spare ratio or the number of mechanics should therefore improve bus dependability.

Table 2 presents the relationships among the spare ratio, number of mechanics, system dependability, average time spent in repair facilities, and average number of buses waiting for repair. Statistics were collected for a duration of 1 year, which covers 223,723 bus-hours of scheduled operation. Results indicate that with the same number of mechanics, as the spare ratio increases, system dependability improves. For the same spare ratio, system dependability also improves with the increase in number of mechanics. Both time spent at the repair shop and length of the queue of buses waiting for repair (LQU) decrease with the increase in number of mechanics. Under the assumptions of the model, maintenance workload depends mainly on total bus mileage, so performance characteristics at the repair shop are not affected by the value of the spare ratio.

Plots of dependability for different numbers of mechanics against different values of the spare ratio are shown in Figure 2 and Figure 3. For a spare ratio of 11.4 percent, system dependability increases from 0.9266 to 0.9662 when the number of mechanics is increased from 5 to 8 in the morning shift and from 3 to 4 in the other two shifts. Similar conclusions

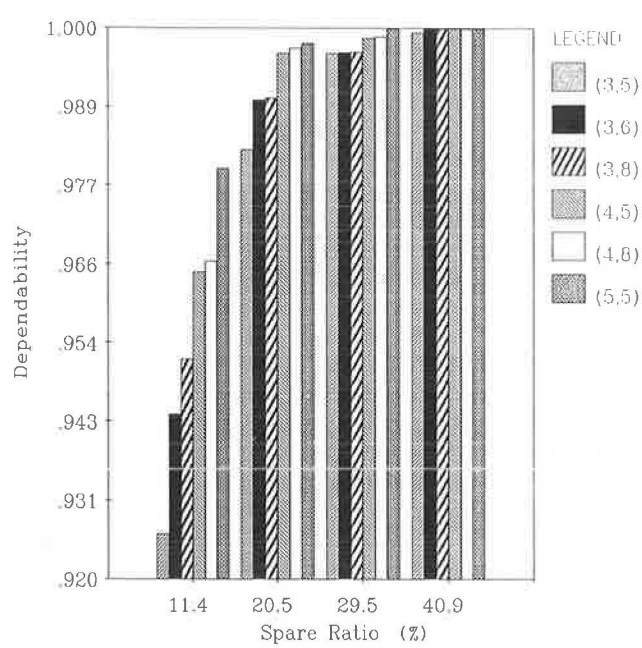

FIGURE 2 Impact of number of mechanics on dependability.

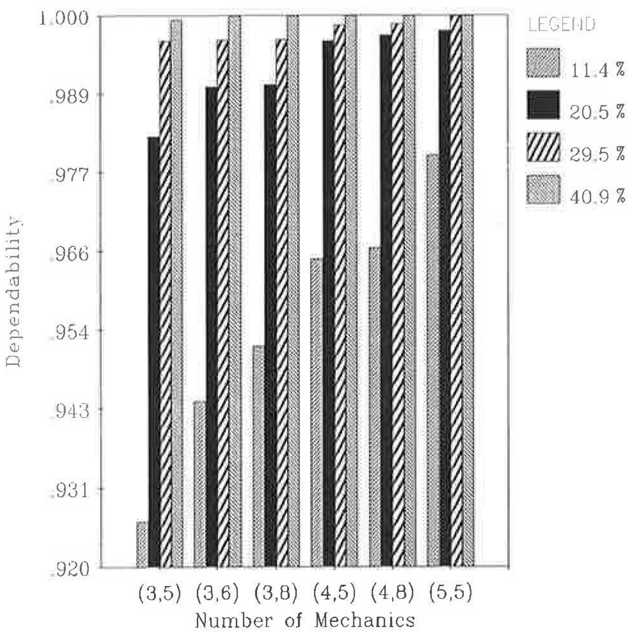

FIGURE 3 Impact of spare ratio on dependability.

TABLE 3 CHANGE IN DEPENDABILITY ASSOCIATED WITH INCREASE IN SPARE RATIO

Number of Mechanics[a]	Spare Ratio (%) 11.4	20.5	29.5	40.9
3, 5	N/A	.0558	.0140	.0030
3, 6	N/A	.0457	.0068	.0035
3, 8	N/A	.0379	.0067	.0034
4, 5	N/A	.0317	.0022	.0014
4, 8	N/A	.0310	.0016	.0012
5, 5	N/A	.0182	.0021	.0000

NOTE: N/A = not applicable (base system)
[a]Evening and night shifts, morning shift.

can be made with the spare ratios of 20.5, 29.5, and 40.9 percent. In addition, for a fixed number of mechanics, system dependability increases with the spare ratio increase.

These results were obtained when the percentage of critical breakdowns of the total number of breakdowns was 25 percent, as estimated by the operators and managers of the system under consideration. The high levels of dependability are not unusual in bus transit systems, where a level of 1.00 is always mentioned as a goal. In fact, a level of 0.98 can be considered low because this means that during 2 percent of the time, one or more buses cannot meet their schedules. In this system, a 0.1 percent change in dependability is translated to 0.001 × 223,723, or about 224 bus-hours of shortage.

Results also demonstrate that, as expected, TISYS and LQU decrease as the spare ratio or the number of mechanics increases. Tables 3 and 4 summarize the incremental change in dependability associated with the increase of the spare ratio and the number of mechanics, respectively.

To decide which combination of spare ratio and mechanics can best fit a system, a formal cost analysis should be performed. Factors such as cost of acquisition, maintenance cost of an additional spare bus, mechanics' salary, and so on should be investigated in the analysis.

Effect of Repair Scheduling Policy

A bus repair system consisting of eight mechanics in the main shift and three mechanics in the other two shifts, 6 days a week, was selected as the base system for all the following analyses. This combination of mechanics was selected because with more mechanics the system would not be sufficiently sensitive to changes in the parameters. A smaller number of mechanics, on the other hand, could cause long queues of buses waiting for repair. The percentage of critical breakdowns used for the base system is 25 percent, and the percentage of time that buses are fixed on location is 50 percent.

The following policies were investigated for repair scheduling:

- First come first served (FCFS);
- Schedule the bus that requires the shortest processing time (SPT) first; and
- For buses that have waited for more than a specific number of hours (8, 16, or 24 hours), use FCFS rule; if none, apply SPT rule.

The results of 20 runs on systems with spare ratios of 11.4 percent, 20.5 percent, 29.5 percent, and 40.9 percent are presented in Table 5 and Figures 4, 5, and 6. Results indicate that a significant improvement can be achieved by applying SPT policy over FCFS. It would be slightly better in most cases to apply the SPT policy and revert back to FCFS whenever one or more buses have been waiting for 16 or more hours.

These results agree, in general, with those obtained by Dutta et al. (*1*), who found that performances of transit systems vary significantly with different repair scheduling policies. They also concluded that systematic scheduling rules

TABLE 4 CHANGE IN DEPENDABILITY ASSOCIATED WITH INCREASE IN THE NUMBER OF MECHANICS

Spare Ratio (%)	Number of Mechanics[a] 3, 5	3, 6	3, 8	4, 5	4, 8	5, 5
11.4	N/A	.0174	.0080	.0127	.0015	.0135
20.5	N/A	.0073	.0002	.0065	.0008	.0007
29.5	N/A	.0001	.0001	.0020	.0002	.0012
40.9	N/A	.0006	.0000	.0000	.0000	.0000

NOTE: N/A = not applicable (base system)
[a]Evening and night shifts, morning shift.

TABLE 5 IMPACT OF REPAIR SCHEDULING POLICY

Spare Ratio (%)	Scheduling Policy	D	TISYS	LQU
	FCFS	0.8780	6.91	2.60
	SPT	0.9420	5.56	1.70
11.4	SPT+8 hrs. Wait Time	0.9250	5.70	1.83
	SPT+16 hrs. Wait Time	0.9580	5.49	1.67
	SPT+24 hrs. Wait Time	0.9280	5.64	1.74
	FCFS	0.9565	6.61	1.79
	SPT	0.9880	5.77	1.82
20.5	SPT+8 hrs. Wait Time	0.9771	5.86	1.84
	SPT+16 hrs. Wait Time	0.9868	5.61	1.87
	SPT+24 hrs. Wait Time	0.9769	5.92	1.89
	FCFS	0.9819	6.63	2.44
	SPT	0.9962	5.46	1.70
29.5	SPT+8 hrs. Wait Time	0.9966	5.52	1.72
	SPT+16 hrs. Wait Time	0.9976	5.78	1.82
	SPT+24 hrs. Wait Time	0.9940	6.01	1.97
	FCFS	0.9953	6.55	2.34
	SPT	1.0000	5.37	1.60
40.9	SPT+8 hrs. Wait Time	0.9996	5.69	1.76
	SPT+16 hrs. Wait Time	1.0000	5.42	1.62
	SPT+24 hrs. Wait Time	1.0000	5.39	1.62

perform better than random scheduling policies and that the application of the SPT rule with limits on the waiting time yields better results than those obtained with other rules. Because the current study indicates a significant advantage of SPT over FCFS and no significant difference between the SPT policy and any of its variations, it was decided to use SPT in all the remaining analyses.

Impact of Rates of Failure

Several factors can affect the rate of failure of individual bus components. These factors include age; environmental characteristics such as climate, terrain, and road conditions; and preventive maintenance policies followed by the system. Independent studies may be performed to estimate the effects of these factors on the rates of failure, but they can be costly and intractable. Alternatively, estimates may be obtained from experienced transit personnel. By adjusting the rate of failure of the individual components, the impact of these factors on the value of the spare ratio and on the overall system performance can be investigated.

The rates of failure observed for the system under consideration were assumed to be average. Two additional levels were investigated for the rates of failure, a higher level with 20 percent more failures and a lower level with 20 percent less. The results are given in Table 6 and in Figures 7, 8, and 9. As expected, all measures of performance demonstrated improvement with lower rates of failure and with higher spare ratios.

tem performance measures should hold true for most systems. These relationships provide valuable information to decision makers and to operators of bus transit systems. The model can also be modified to simulate the operations of different bus transit systems.

ACKNOWLEDGMENT

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REFERENCES

1. U. Dutta, T. H. Maze, and A. R. Cook. Effectiveness of Improved Repair Scheduling in the Performance of Bus Transit Maintenance. In *Transportation Research Record 1066*, TRB, National Research Council, Washington, D.C., 1986, pp. 46–59.
2. H. G. Wilson. *Forecasting Bus Transit Operating Costs*. Report PB-262634. Pennsylvania State University, University Park, November 1975.
3. K. C. Sinha and A. S. Bhandri. *A Comprehensive Analysis of Urban Bus Transit Efficiency and Productivity*. UMTA, U.S. Department of Transportation, 1978.
4. R. W. Drake and D. W. Carter. Evaluation of Bus Maintenance Manpower Utilization. In *Transportation Research Record 1019*, TRB, National Research Council, Washington, D.C., 1985, pp. 49–62.
5. R. L. Jackson, G. A. Coe, and A. J. Finnanore. *A Study of Some Factors Affecting Bus Service Performance*. Report 767. Transport and Road Research Laboratory, Crowthorne, Berkshire, England, 1977.
6. D. Koffman. A Simulation Study of Alternative Real-Time Bus Control Strategies. In *Transportation Research Record 663*, TRB, National Research Council, Washington, D.C., 1978, pp. 41–46.
7. R. P. Guenthner and K. C. Sinha. Maintenance, Schedule Reliability and Transit System Performance. *Transportation Research*, Vol. 17A, No. 5, 1983, pp. 355–362.
8. T. H. Maze, A. R. Cook, and U. Dutta. *Bus Fleet Management Technique Guide*. Oklahoma Highway and Transportation Engineering Center, University of Oklahoma, Norman, August 1985.
9. T. H. Maze and U. Dutta. Estimating Bus Component Failure Distributions from Censored Samples. *Transportation Research*, Vol. 18B, No. 3, 1984, pp. 201–208.
10. M. Kosinski, J. F. Foerster, and F. G. Miller. *Development of Transit Bus Component Failure Statistics from Conventional Bus Card Records*. Urban Transportation Center, University of Chicago at Chicago Circle, Chicago, Ill., 1982.
11. UMTA. *DOT Needs Better Assurance that Transit Systems are Maintaining Buses*. Report GAO/RCED 83-57. U.S. Government Accounting Office, 1983.
12. T. H. Maze, U. Dutta, and M. D. Kutsal. Role of Quantitative Analysis in Bus Maintenance Planning. In *Transportation Research Record 915*, TRB, National Research Council, Washington, D.C., 1983, pp. 39–48.
13. T. H. Maze, G. C. Jackson, and U. Dutta. Bus Maintenance Planning with Computer Simulation. *Journal of Transportation Engineering*, Vol. 109, No. 3, May 1983.
14. L. A. Martin-Vega. SPT Data Analysis, and a Bit of Common Sense in Bus Maintenance Operation: A Case Study. *AIIE Transactions*, December 1981, pp. 349–356.
15. A. B. Pritsker. *Introduction to Simulation and SLAM II*. John Wiley and Sons, New York, 1986.
16. W. H. Iskander and M. Jaraiedi. *An Evaluation of the Spare Ratio Concept in the Management of Transit Rolling Stock*. Report No. WV-11-0004, UMTA, U.S. Department of Transportation, 1988.

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