Sensitivity to Various Parameters of a Demand-Scheduled Bus System Computer Simulation Model

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A computer simulation model has been developed that simulates a demand-scheduled bus system offering door-to-door service. Sensitivity analyses were performed on various parameters in the model. The parameters studied were link travel time, maximum pickup time, shape of serviced area, frequency of calls, bus capacity, and length of trips. The outputs considered sensitive to a change in these parameters were cost of operation per passenger-mile, waiting time to be picked up, passenger travel time on the system, and the total time required to make a trip.

In general it was found that, as the link travel time increased, the cost per passenger-mile rose sharply, the waiting time was relatively constant, the travel time moderately increased, and the total time required to complete a trip also increased moderately. As the maximum pickup time increased, the cost per passenger-mile decreased; and the waiting, travel, and total time increased linearly. The shape of the geographical area served did not influence the waiting, travel, and total time as might be expected.

As the demand for service increased, the waiting time remained relatively constant; the travel time and total time had only a slight increase and then leveled off. The cost per passenger-mile decreased significantly up to a demand of approximately 175 calls per hour and then began to level off. The total operating cost of the system increased with an increase in demand for service. An increase in bus capacity had little effect on the waiting, travel, and total time. However, there was a slight decrease in cost per passenger-mile with an increase in bus capacity. When short trips (1 to 4 blocks) were excluded from being served, the cost per passenger-mile decreased somewhat. The waiting time remained relatively constant, but the travel and total time had a slight increase.

•THE RESTORATION of public transportation to a place of prominence in urban areas has become a pressing and perplexing problem facing transportation planners. Mounting evidence of steadily declining ridership is an indication that conventional transit modes do not meet the needs of current situations. Thus, a vast number of proposals for new transit modes has appeared in recent years. These proposals vary widely in scope, complexity, feasibility, and cost; they range from those that would tend to alter urban development to those that make more modest marginal improvements in existing techniques. One such proposal (BUSTOP) is that of a demand-scheduled bus system; the operational characteristics are discussed by Heathington, Miller, Knox, Hoff, and Bruggeman (1).

The concept of a demand-scheduled bus (DSB) system falls more nearly into the latter group of proposals that make marginal improvements. Requiring few major technological developments and operating on existing city streets, a DSB system will neither create havoc in the existing urban structure nor require exorbitant funding to

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implement. On the other hand, a DSB system will not be able to supplant the automobile, although it can help to relieve congestion at crucial times and locations.

Although the actual operation and control of a DSB system differs among various proposals, the underlying concept is that a transit system can be developed that utilizes small bases that operate on local streets and respond to a specific call for service (1, 2, 3, 4). Such service would thus be similar to that provided by taxicabs, except that savings in cost can accrue by assigning more than one passenger to a vehicle.

Several different control schemes have been proposed, but it is now generally accepted that some type of computer control is needed in order to assign a passenger more efficiently to one of several available vehicles. Several different types of service have also been proposed, such as the so-called many-to-one system of diffused origins and a single destination (3). The most general scheme of diffused origins and destinations, the many-to-many system, has been proposed and is developed in more detail in this report (1).

Although the notion of a demand-scheduled bus system had been conceived some years before, the idea did not become popular until the publication of the details of the Genie system proposed at MIT in 1966 as part of Project Metran (2, 3). In the short time since then, much interest and attention has been given to further research on DSB systems at MIT and elsewhere (4). General Motors included an evaluation of a Genie-type system as part of its research on furture urban transportation technology (5). General Research Corporation has worked on developing an analytical model of the Genie performance (6). All of these studies have concentrated on the many-to-one system mentioned above.

DEVELOPMENT OF BUSTOP

In April 1967, a group of transportation researchers at Northwestern University conceived of the idea of developing a generalized computer simulation model of a DSB system offering service to diffused origins and destinations (the many-to-many problem). It was felt that the potential of a DSB system was much broader than that of one serving only as a feeder to a line-haul transit station or some other high-demand location. A DSB system can, it is hoped, not only provide service to those people without access to an automobile but also divert some marginal automobile users. In addition, an investigation of the many-to-one problem could easily be carried out with a more general model that simulates the many-to-many problem.

The results of this effort, known as Project BUSTOP, go into greater detail about the need for and use of a demand-scheduled bus system. The present paper concerns itself with some sensitivity analyses of the specific simulation model previously developed.

BUSTOP employs a different control philosophy than that of the Genie model that imposes a rather rigid set of vehicle requirements and operating rules and obtains passenger service as an output. This has the effect of giving fair control over the operating costs of the system, but little guarantee regarding service to the customer. BUSTOP, on the other hand, specifies a rather strict set of passenger service criteria, which can be altered parametrically, and determines the system requirements as output. This approach seems more appealing if one is to develop a public transportation system in competition with other modes.

Specifically, the control logic specifies a minimum and maximum time (MINP, MAXP) for a passenger to be picked up after his call is received. Then, a latest possible delivery time is calculated from the maximum pickup time plus a travel time depending on the length of the trip. This travel time is equal to twice the link travel time (LTT) between origin and destination for trips under a mile (10 links), and 5 min plus the link travel time for trips over a mile. This decision rule can be varied parametrically as desired.

The service area selected is that of a rectangular grid network with constant travel times on each link. Vehicle control is maintained by a simple "first north, then east" rule that is acceptable because of the assumption that travel times are equal in all directions. For initial calibration, a square mile area was chosen with 9 blocks to the mile and a link travel time of 30 sec, corresponding to an overall speed of 13 mph. All these quantities can be varied parametrically within the model.

Any demand distribution can be accepted as an input to the model. For simplicity, a uniform distribution of calls over a given time period was chosen, as well as a uniform distribution of origins and destinations. As mentioned above, the many-to-one problem can be simulated by substituting a single location for all destinations. Similarly, a high-demand strip development can be simulated by adjusting the demand distribution to reflect such activity.

It is assumed that all vehicles are located initially at a central terminal, from which they are "generated" as needed. Passengers are assigned to the closest vehicle that can service them without violating the time constraints of any other committed passengers. Pickup and delivery may be made in any order, and all possible combinations are tested. Only if none of the vehicles on the system can service the passenger is a new vehicle generated. When a vehicle has delivered its last assigned passenger, it returns to the terminal and becomes the first to be "regenerated" when a call situation requires an additional vehicle.

No attempt at "optimal" assignment has yet been made. Because of the stochastic processes within the model, an optimal assignment at any given time is likely to be less than optimal after the next call is received. Likewise, no consideration to reassigning passengers has been made; once a passenger has been assigned to a vehicle, that vehicle is obligated to pick up and deliver him. Assignments on an optimal basis might prove to be worthwhile; however, the effect of reassignment on passenger level of service is a very difficult question to answer and probably should await the development of a model to predict demand.

SENSITIVITY ANALYSIS

It is believed that the development of a workable DSB system should proceed in three phases. The first phase is the development and application of a large-scale computer simulation model of a DSB system. Through sensitivity analyses on the model, the influence of many parameters can be evaluated, which would not be feasible in a field-test situation.

Parallel to the development of the simulation model should come the development of a demand model for passenger usage of the system. This model must be sensitive to changes in the various control parameters of the simulation model, as they affect passenger demand. These parameters must include not only absolute quantities such as waiting and travel time but also such things as reliability of service.

The third phase must be the development of adequate cost data based on various levels of hardware requirements, control procedures, and levels of service. Only after these three steps have been completed should a full-scale demonstration or operational project be undertaken.

The response or sensitivity of the simulation model to changes in various parameters is one of the most basic studies needed to be undertaken. Some preliminary sensitivity investigations of the primitive model discussed above were undertaken in an attempt to get at these responses. Although the simulation model under consideration is much simpler than that of an actual proposed operating system, it is felt that some valuable insight into the operation of such a system was gained.

Several of the parameters mentioned above were varied, one at a time, and the output from the model recorded. The simulation period chosen was one hour of real time. Operation of an "up-and-down" situation was studied; that is, the simulation was started "cold" with all vehicles in the terminal and was continued past the one-hour cutoff point for calls until all passengers were delivered and the vehicles had returned to the terminal. Other simulation techniques could have been chosen, such as a "steady-state" period out of the middle of the simulation run or perhaps a cutoff of the simulation at the end of the hour. The up-and-down technique was selected, however, because it was desired to study the behavior of the model under both of the end situations.

Output from the model is in two forms: passenger data and vehicle operation data. Passenger data consist of average waiting, travel, and total time per passenger on the system and are presented here directly in that form. These results could be used as feedback to a demand model in order to determine the effect of different passenger statistics on generated demand. The distribution of these service times was also available but was not used in this analysis, although it would form a measure of system dependability as an input to a demand model.

Vehicle performance data were mainly of two types: total number of vehicles used and total number of vehicle-minutes on the system. Vehicle occupancy, because it is a transitory phenomenon in DSB operation, was not judged to be a meaningful output. For purposes of presentation, these vehicle output results were converted to crude operating costs. Vehicle costs were assumed to be $5,000, amortized over a 10-year period at 6 percent interest, and based on usage of only 4 peak hours per day (1,000 hours per year). Driver-labor cost was set at $3.00 per hour per vehicle generated and came to $3.35 per simulation period that allowed for an average of 7 extra minutes required by the up-and-down operation. Finally, a cost of 2.2 cents per vehicle-minute, corresponding roughly to 12 cents per vehicle-mile, was selected to cover the cost of vehicle operation. Additional costs, such as garage facilities at the terminal, control facilities, taxes, licenses, and administration, were felt to be relatively constant over the range of situations considered and were not included in the evaluation.

These costs are meant to be only illustrative. For this reason, the actual output from the various simulation runs is included in the Appendix so that the reader may insert more precise estimates of costs and achieve a more meaningful cost evaluation. Such evaluations however, will only alter the magnitude of the relationships here presented; the fundamental nature should remain relatively unchanged.

Each data point included in the Appendix and used in the analysis is the average of 5 runs of the simulation model with different "seeds" for the random generation of calls. However, the set of calls is the same between points that are based on the same number of calls and size of area. A total of 4 data points was calculated from each run of the simulation model, which took, at a call frequency of 100 per hour, roughly 105 sec of central processor time on a CDC 6400 computer. This means that data for over 20 hours of real time were obtained in just over a minute and a half of computer time, with no attempt made at optimizing the existing FORTRAN IV code. The time increased roughly proportionally with an increase in call frequencies.

Several input parameters to the model remained invariant throughout all the simulation runs. The minimum waiting time was set at 1 min and the loading and unloading time at 15 sec. It was not felt that realistic selection of other values for these parameters would be of sufficient magnitude to noticeably affect the result. The simple travel-time rule discussed above was used throughout, although other rules could have certainly been incorporated. No runs were made with other than uniform call distributions.

SIMULATION RESULTS

The first parameter investigated was link travel time. Values from 18 sec (22 mph) to 36 sec (11 mph) were chosen. (These different travel times could be interpreted equally well as resulting from closer street spacing and hence a smaller area.) Two slightly different service policies were selected: the first was based on a division between long and short trips by distance, and the second was based on a time value of 5 min. Both are equivalent with a link travel time of 30 sec. The results for the two cases differed only slightly and are shown in Figure 1. Cost per passenger-mile rose steeply with increasing travel time, as expected. Average waiting time increased very little, which was somewhat surprising, and remained approximately half of the maximum value of 6 min. Travel time increased linearly, and total time, of course, followed the same general shape.

The effect of changing the maximum allowable waiting time was not as well defined. The cost of operation showed a tendency to decrease, though not nearly as much as might be anticipated, and the variation about the line shown in Figure 2 was quite high. Of equal interest was the behavior of the passenger time distributions. All three closely followed a linear pattern. The average waiting time increased, although much

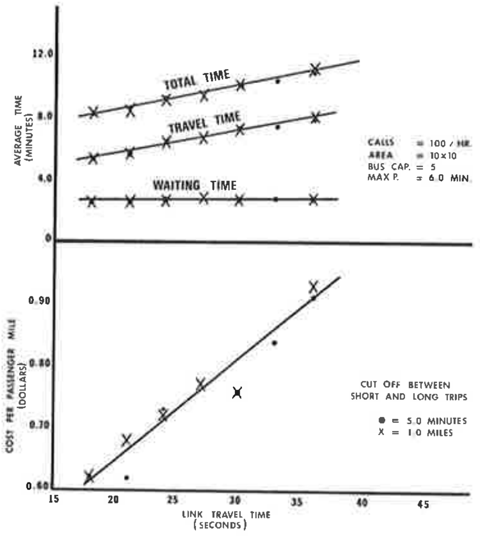

Figure 1. Sensitivity to changes in link travel time.

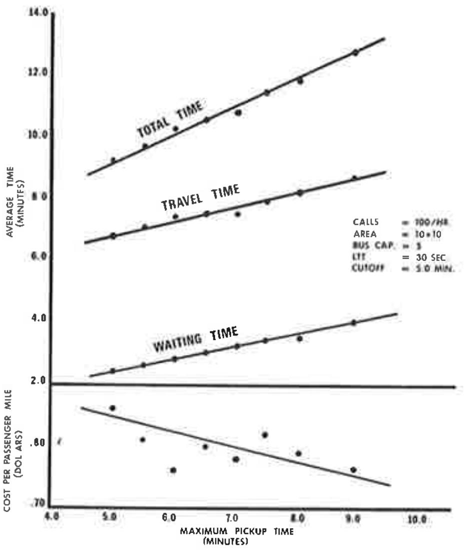

Figure 2. Sensitivity to changes in maximum pickup time.

less rapidly than might have been anticipated. More remarkable, however, is the fact that the average travel time increased slightly more sharply than the waiting time, even though no changes were made in travel parameters. This indicates a higher flexibility in vehicle routing, although at a significant inconvenience to passengers already assigned. Thus, only a very minor cost savings developed, possibly at the expense of a considerable reduction in patronage caused by the increased travel time, plus the added uncertainty as to actual pickup time. The results seem to indicate, at least for the demand used here (100 calls per hour), that increasing the maximum pickup time would not be a profitable change in system operating characteristics.

A third analysis was performed using differently shaped areas and the results are shown in Figure 3. The areas selected were just slightly smaller than the basic 10 by 10 grid used in the other analyses. Although a slight increase in cost per passenger-mile over the square area was noted, no further increase was detected even for quite elongated shapes. Almost no change in passenger output was detected among any of the areas. These results are rather significant in that they show that DSB operation in districts of different shape, but similar land area, will be almost identical. One difficulty, of course, is that in extremely elongated areas, either (a) the service to the extreme points must be lowered, (b) a rather high uniform maximum pickup time must be set, or (c) more than one vehicle "generator" must be provided. The latter is probably the preferred solution.

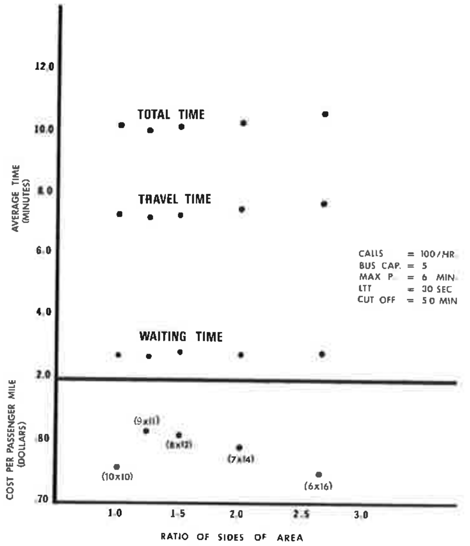

Figure 3. Sensitivity to changes in shape of area.

Demands of from 50 to 250 passengers per hour were examined. The results shown in Figure 4 indicate that the total operating cost increases linearly beyond 75 passengers per hour. However, the

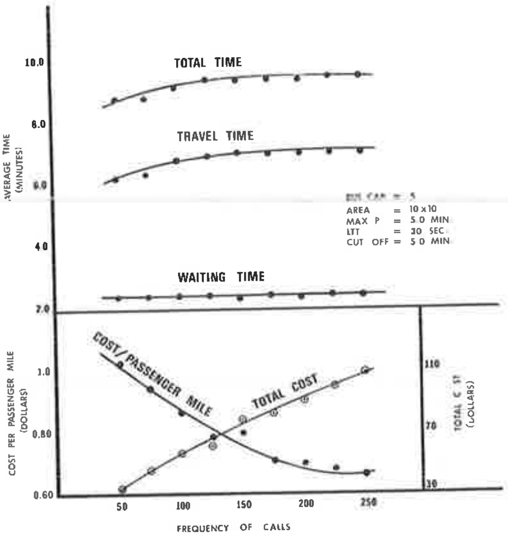

Figure 4. Sensitivity to changes in demand.

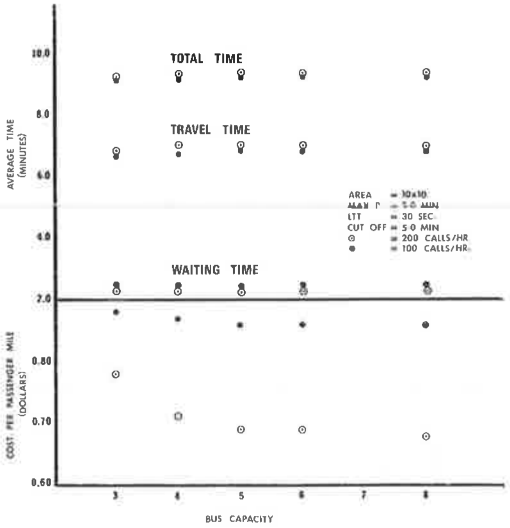

Figure 5. Sensitivity to bus capacity.

average cost per passenger-mile decreases significantly up to about 200 passengers per hour, beyond which little change occurs. The effect on passenger service is rather interesting. No effect on average waiting time was observed. Travel time was found to increase slightly up to about 150 calls per hour, after which no effect was observed. These results seem to indicate that the system will provide virtually identical service over a fairly wide range of demands.

The effect of vehicle size was examined at two different demand levels: 100 and 200 calls per hour. Figure 5 illustrates the results. The cost figures here are somewhat spurious, because it was assumed that the capital and operating costs for the different size vehicles were the same. Again, the reader is referred to the data in the Appendix for use in determining the cost functions for different vehicle sizes based on different unit operating costs. At 100 calls per hour, so few buses are ever filled that only a very slight increase in equipment is required when three- and four-passenger vehicles are used. At 200 calls per hour, a more noticeable variation in necessary equipment of different sizes was noted, although the advantages of six- and eight-passenger vehicles over five-passenger ones were very small. However, the expected cost per passenger-mile was much lower in all cases at the higher demand level and indicated higher utilization of available vehicle capacity. Passenger output showed almost no appreciable change among vehicle sizes or among different call frequencies. Although insufficient data are available for any really meaningful conclusions, one might infer that, for any given demand level, an increase in vehicle capacity beyond a certain point will not improve system performance. However, any cost savings involved in using a minimum size vehicle must be offset against the loss in flexibility potential.

Finally, it was hypothesized that model performance would be improved if unrealistically short trips were excluded from the analysis. This was examined by successively eliminating all trips of under 1, 2, 3, and 4 blocks in length. Call frequencies of 100 and 200 calls per hour were generated for each case, and the results are shown in Figure 6. Although total operational cost changed very little, the cost per passenger-mile increased when only the shortest trips were eliminated and then decreased steadily as longer trips were eliminated. Passenger waiting time remained virtually constant, but travel time increased slightly, reflecting the increased desired travel distance.

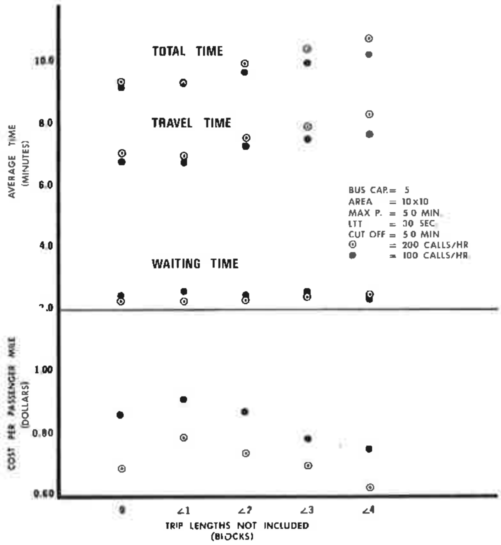

Figure 6. Sensitivity to reduction in short trips.

MODEL PERFORMANCE

The output of the model in terms of cost is most closely tied to driver salary. This is an unfortunate inevitability in DSB operation, because such a system cannot be readily automated as can a more conventional rail system. Also, a critical element here is the generation of an additional vehicle to meet a specific demand. Although possibly needed for only one passenger, the vehicle remains on the system and lowers the overall passenger-to-vehicle ratio for all other vehicles. Perhaps some form of a buffer should be established in the model to raise the allowable pickup time for a call that would otherwise cause a new vehicle to be generated. Although this would reduce overall system reliability, the cost savings might be worthwhile. An alternative is to have some vehicle, designated as an "emergency" vehicle, that would respond to calls only when no other vehicle can handle them; this vehicle would not be checked for availability under normal circumstances. Any of these variations could be readily incorporated into the model, although a meaningful evaluation of their effect could be difficult without a highly sensitive demand model.

Other system alterations could be incorporated. The insertion of irregular, though reasonably well-behaved, boundaries or barriers could be made. The coding of an actual street system with varying link travel times is not possible at this stage in the model development, but the use of average times with a reasonably small list of special situations could be incorporated. Thus, operation on a real street system might be roughly approximated, without the development of a general model, although the size of the service area might have to be rather small.

Sophisticated alterations on the demand side, including varying demand temporally or spatially, the inclusion of priorities or varying service levels, or the use of special purpose vehicles for different trip types could be incorporated with varying levels of difficulty. Once again the evaluation of such situations could require a highly sophisticated demand model and a much more adequate set of system operating costs.

Although the output seems to indicate that such a system will be quite costly, even with the assumption that there is a low unit cost, it should be noted that an extremely high level of service has been maintained. Also, a quite small area and very low demands have been used, which do not allow for any economies of scale. Likewise, the assumption that demand distribution is uniform, though the most general, is probably also the most inefficient, because it does not provide for economies in concentrating origins and destinations. Further investigation of these and other extensions must await the development of a more sophisticated model.

CONCLUSIONS

In general, the results of this study show that a very flexible, highly efficient simulation model of a demand-scheduled bus system can be constructed and operated for the many-to-many problem. Parametric examination of the model yields the significance of various control parameters in determining system efficiency. The model is highly sensitive to link travel time, but is relatively insensitive to the maximum allowable pickup time or the shape of the area. The effect of vehicle size does not seem to become apparent until a substantial number of vehicles are operating at capacity. Finally, the cost per passenger-mile decreases with increasing demand,but appears to approach some minimum value under a given set of system characteristics.

Authors' Note—Since this paper was written, a U.S. Department of Housing and Urban Development publication on DSB operation has appeared in the series "Study in New Systems of Urban Transportation." This publication, "Study of Evolutionary Urban Transportation," was prepared by Westinghouse Air Brake Company (WABCO) and others. Although a considerably different algorithm was used, the findings quite noticeably support those of this paper. In addition, the WABCO report contains considerable cost data that might be applied to the simulation results contained in the Appendix of this paper.

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Appendix

The summary of simulation runs are given in the following table. Maximum pickup time (Maxp), link travel time (LTT), and cutoff point (COP) are shown in minutes. Waiting time, travel time, total time, and bus-minutes are totals for all passengers and vehicles over the simulation period. The total amount of desired travel (Lnks) is given in blocks. Gross occupancy (Occ.) is given as the ratio of passenger-minutes to bus-minutes. (Passenger-minutes is the same as total travel time.)

SUMMARY OF SIMULATION RUNS

Run	Calls	B-Cap	Area	Maxp	LTT	COP	Lnks	Wait	Trvl	Totl	Bus	B-Min	Occ.
1	100	5	10x10	6.0	0.30	5.0	658	263	557	819	8.2	360	1.57
2	100	5	10x10	6.0	0.40	5.0	658	270	651	921	9.6	445	1.48
3	100	5	10x10	6.0	0.50	5.0	658	280	736	1017	9.8	504	1.47
4	100	5	10x10	6.0	0.60	5.0	658	297	799	1096	11.6	612	1.31
5	100	5	10x10	5.0	0.50	5.0	658	241	678	919	11.2	533	1.28
6	100	5	10x10	6.0	0.50	5.0	658	280	736	1017	9.8	504	1.47
7	100	5	10x10	7.0	0.50	5.0	658	323	755	1077	10.0	500	1.52
8	100	5	10x10	8.0	0.50	5.0	658	359	824	1183	10.2	516	1.61
9	100	5	10x10	5.5	0.50	5.0	658	259	702	961	10.4	519	1.36
10	100	5	10x10	6.5	0.50	5.0	658	300	752	1052	10.4	511	1.48
11	100	5	10x10	7.5	0.50	5.0	658	345	796	1141	10.6	525	1.53
12	100	5	10x10	9.0	0.50	5.0	658	404	878	1281	9.6	529	1.67
13	100	5	9x11	6.0	0.50	5.0	657	278	723	1002	10.6	516	1.41
14	100	5	8x12	6.0	0.50	5.0	662	288	730	1018	10.6	504	1.46
15	100	5	7x14	6.0	0.50	5.0	686	280	747	1027	10.6	518	1.45
16	100	5	6x16	6.0	0.50	5.0	722	287	773	1060	10.6	519	1.50
17	100	5	10x10	6.0	0.30	3.0	658	271	553	825	8.2	354	1.58
18	100	5	10x10	6.0	0.40	4.0	658	271	653	924	9.4	447	1.47
19	100	5	10x10	6.0	0.45	4.5	658	284	668	952	10.0	489	1.38
20	100	5	10x10	6.0	0.60	6.0	658	297	813	1111	12.0	605	1.35
21	75	5	10x10	5.0	0.50	5.0	500	188	477	665	9.4	422	1.14
22	150	5	10x10	5.0	0.50	5.0	979	355	1053	1407	15.4	731	1.59
23	200	5	10x10	5.0	0.50	5.0	1301	473	1396	1869	17.4	912	1.55
24	250	5	10x10	5.0	0.50	5.0	1630	600	1773	2372	20.6	1117	1.61
25	50	5	10x10	5.0	0.50	5.0	332	121	318	440	6.8	296	1.08
26	125	5	10x10	5.0	0.50	5.0	820	315	859	1175	12.4	637	1.37
27	175	5	10x10	5.0	0.50	5.0	1143	429	1222	1651	15.6	822	1.50
28	225	5	10x10	5.0	0.50	5.0	1457	545	1587	2133	18.6	1045	1.54
29	100	3	10x10	5.0	0.50	5.0	658	247	660	907	11.4	542	1.23
30	100	4	10x10	5.0	0.50	5.0	658	241	675	916	11.4	535	1.27
31	100	6	10x10	5.0	0.50	5.0	658	241	678	919	11.2	533	1.28
32	100	8	10x10	5.0	0.50	5.0	658	241	678	919	11.2	533	1.28
33	200	3	10x10	5.0	0.50	5.0	1301	470	1360	1830	20.0	982	1.40
34	200	4	10x10	5.0	0.50	5.0	1301	475	1394	1860	17.8	935	1.51
35	200	6	10x10	5.0	0.50	5.0	1301	477	1394	1871	17.2	923	1.53
36	200	8	10x10	5.0	0.50	5.0	1301	473	1388	1861	17.0	916	1.54
37	100	5	10x10	6.0	0.35	5.0	658	267	605	872	8.0	389	1.57
38	100	5	10x10	6.0	0.55	5.0	658	298	753	1051	10.8	547	1.39
39	100	5	10x10	6.0	0.35	3.5	658	264	596	860	8.8	402	1.50
40	100[a]	5	10x10	5.0	0.50	5.0	682	254	676	931	12.2	593	1.18
41	100[b]	5	10x10	5.0	0.50	5.0	713	242	728	971	12.4	582	1.26
42	100[c]	5	10x10	5.0	0.50	5.0	754	251	746	997	11.4	587	1.28
43	100[d]	5	10x10	5.0	0.50	5.0	793	239	781	1020	11.6	582	1.34
44	200[a]	5	10x10	5.0	0.50	5.0	1337	460	1390	1849	20.4	1029	1.37
45	200[b]	5	10x10	5.0	0.50	5.0	1421	477	1503	1980	20.6	1059	1.43
46	200[c]	5	10x10	5.0	0.50	5.0	1525	499	1577	2076	21.4	1060	1.50
47	200[d]	5	10x10	5.0	0.50	5.0	1620	484	1670	2154	19.6	1057	1.59

[a] No calls less than 1 block included.

[b] No calls less than 2 blocks included.

[c] No calls less than 3 blocks included.

[d] No calls less than 4 blocks included.