# Transit Route Characteristics and Headway-Based Reliability Control

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ABSTRACT

Previous research has provided a method for improving transit service reliability through headway-based control by using models developed and validated from empirical data. In implementing this strategy, identification of transit routes the characteristics of which can potentially yield significant reductions in passenger wait time is a critical issue. In this paper, several characteristics of the transit route are examined to identify the most appropriate conditions under which headway-based control should be exercised. The paper includes an evaluation of several boarding and alighting profiles that typify ridership characteristics of metropolitan bus systems, sensitivity analyses to determine if small boarding changes or increased volumes affect the benefits of headway-based control, the effects of changes in the weight assigned to passengers detained at the control stop compared with those waiting downstream, the impact of initial headway variation at the route origin, and the effect of parking considerations along a route. The results indicate that profiles with passengers boarding at the middle and alighting at the end of a route produce the most significant savings in passenger wait time when headway-based control is implemented. Improvements in wait-time reduction diminish as more passengers board at early stops and are enhanced as the total ridership increases. Increases in the initial headway variation and amount of parking permitted along a route help deteriorate route reliability and thus improve the effectiveness of implementing a control strategy. The effect of assigning more importance to passengers detained at the control point compared with passengers waiting downstream of control decreases the effectiveness of implementing a headway-based control strategy, as expected. Collectively, the findings are intuitively appealing and suggest preferred conditions under which headway-based control is a viable operating strategy.

Previous research concerning transit service reliability has produced a method for maintaining regular service intervals through headway-based control by using models developed and validated from empirical data.

A headway-based strategy consists of holding a bus at a specified location for a certain amount of time, known as the threshold value (X). If the headway between the previous bus and the arriving bus is less than X, the arriving bus is held up to X. If this headway is greater than X, the arriving bus is not held. Headway-based control is most suitable for routes operating with short, uniform headways. When headways are short and uniform, it is assumed that passengers arrive more randomly at stops and that they are more concerned with the headway than with the schedule. Similarly, operators are concerned about keeping vehicles evenly spaced so that vehicle availability remains stable and the need to assign additional vehicles to a route is diminished.

Considerable detail on a decision algorithm for headway-based control has been documented previously in the literature, and thus will only be described briefly in this discussion (1). The methodology consists of five sequential steps:

1. Derivation of mean running time,
2. Estimation of running time variation,
3. Computation of headway variation,
4. Determination of passenger wait time, and
5. Implementation of optimal control strategy.

The first four steps represent the derivation of models developed and validated from empirical data of bus operations in metropolitan Cincinnati and Los Angeles. These model outputs feed into Step 5, where the feasibility of control is determined. If control is deemed effective, the optimal stop and threshold levels are determined. This is based on an algorithm designed to minimize the following objective function:

$$TW = \sum_{i=1}^{j-1} (n_i \times \bar{w}_i) + [b_j \times d_j(x)] + \sum_{i=j}^{N} (n_i \times \bar{w}_i) \qquad (1)$$

where

$TW$ = expected total wait time on route,
$j$ = control stop,
$n_i$ = number of passengers boarding at stop i,
$\bar{w}_j$ = average wait time at stop i,
$b_j$ = number of passengers on board at stop j,
$d_j(x)$ = expected delay at the control stop for the threshold of x,
$x$ = threshold value, and
$N$ = total number of stops on route.

Although minimization of total wait time is the objective of the algorithm, achieving this objective also creates a more regular interval of vehicle ar-

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LIST OF EFFECTIVE CONTROL STOPS BY ORDER

STOP 6,  THRESHOLD  4.00 MIN,  REDUCTION  11.82 MIN,  %REDUCTION  8.37%

STOP 5,  THRESHOLD  4.00 MIN,  REDUCTION  11.28 MIN,  %REDUCTION  8.00%

STOP 4,  THRESHOLD  4.00 MIN,  REDUCTION  10.67 MIN,  %REDUCTION  7.57%

STOP 3,  THRESHOLD  4.00 MIN,  REDUCTION  10.17 MIN,  %REDUCTION  7.21%

STOP 2,  THRESHOLD  4.00 MIN,  REDUCTION  9.51 MIN,  %REDUCTION  6.74%

STOP 7,  THRESHOLD  2.25 MIN,  REDUCTION  2.27 MIN,  %REDUCTION  1.61%
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**FIGURE 1** Sample output for headway-based control.

rivals, which reduces the number of vehicles required to effectively cover a route. Thus, the wait-time reductions that are reported subsequently in this paper should be considered as a measure of both passenger benefit and operator benefit.

To facilitate policy analysis, the entire methodology has been coded in PASCAL for microcomputer application. For each stop, the user defines the number of boardings and alightings, distance and number of intersections from the previous stop, direction and time period of travel, and, if available, the percentage of on-street parking allowed from the previous stop. The user is also prompted for additional information concerning the weight assigned to passenger delay for persons on-board a vehicle if control is implemented compared with passenger wait time for persons waiting to board the vehicle downstream of the control stop. This latter consideration allows for the specification of different impedances for different types of passenger delay.

The model output includes a priority listing of the most effective control stops on the route with their corresponding threshold values and the benefits of control over the no-control case [see Figure 1; reduction = total passenger wait-time reduction, threshold = threshold value (X), and headway = 4 min]. A previous validation of the methodology and algorithm was conducted by using data from the Southern California Rapid Transit District (SCRTD) and reviewing the predicted results with the SCRTD Scheduling Department. For each route analyzed, the percentage of reduction in the total wait time predicted by the methodology was considered reasonable.

The primary objective of continuing this research was to evaluate the sensitivity of headway-based control to varying boarding and alighting profiles, headways, and other characteristics of route operations. The study also involved separate analyses concerning the effect of changing the initial headway variation (to reflect bus dispatching irregularities) and the weight assigned to passengers detained at the control stop compared with passengers waiting downstream of the control point. An interest in determining which factors produce significant reductions in total passenger wait time under headway-based control was a motivating factor in the research.

## ANALYSIS RESULTS

The following general boarding and alighting profiles were established to investigate the impact of ridership profiles on the effectiveness of headway-based control (see Figure 2):

- Boarding at the beginning of the route and alighting at the end.
- Boarding at the beginning of the route and alighting at the middle and end.

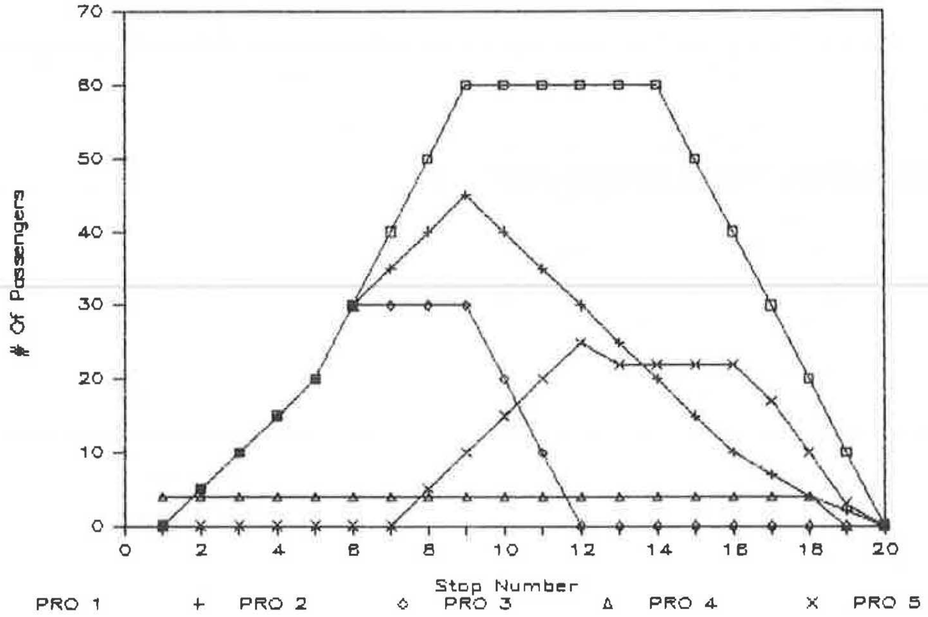

**FIGURE 2** On-board profile of passengers for each scenario.

- Boarding at the beginning of the route and alighting at the middle.
- Boarding and alighting uniformly along the route.
- Boarding at the middle of the route and alighting at the end.

The first scenario represents routes that originate in the suburbs and end in the central business district (CBD) during the morning peak period and originate in the CBD and end in the suburbs during the afternoon peak period. Scenario 2 represents routes similar to Scenario 1; however, some passengers on this type of route alight before the CBD during the morning peak period or before the suburban route terminus in the afternoon. Routes that originate in the suburbs and pass through the CBD in the middle of their route are represented by Scenario 3. The fourth scenario represents a type of route operating solely in the CBD, where passengers are uniformly boarding and alighting at each stop. The fifth scenario represents routes that start before the CBD and end in the suburbs during the afternoon peak period.

For the purpose of creating a uniform basis of comparison, evaluation of each boarding and alighting scenario was conducted by using a 20-stop route with a total of 60 passengers boarding and alighting; all other parameters were held constant. When control is effective, the optimal control stop is identified by the algorithm and its corresponding threshold value is computed. The threshold value is highly dependent on the number of passengers on board at the control stop because they will incur delay time if the bus is held. Threshold values usually range from the scheduled headway to one-half of the headway for effective control strategies. When control is not deemed to be effective, the threshold value approaches zero.

Headway-based control proved to be ineffective for those profiles that had passengers boarding at the beginning and alighting at the end, middle, or middle and end of a route. For Scenarios 1 to 3, passengers are boarding the bus during the first few stops. Regardless of where these passengers alight, the reduction in total passenger wait time associated with implementing a control strategy is negligible. Control is not effective under these conditions because of the lack of passengers boarding downstream and the relatively large number of people on board the bus at any potential control point. If there are no passengers waiting downstream of the initial boardings, there is no benefit to passengers waiting downstream by holding buses. Rather, additional delays are sustained by passengers detained on board the bus at the holding point. These results were consistent across headways ranging from 4 to 10 min. Scenarios 4 and 5 demonstrated encouraging results and warranted additional examination.

Unlike the first three scenarios, the uniform boarding and alighting profile included passenger boardings at almost every stop (see Figure 3; in this figure, headway = 4 min; control stop = 12; X = 1.75 min; and percent reduction = 1.00). Reductions in wait time occurred for this profile because enough passengers were waiting downstream who would benefit from the use of a control strategy. However, these reductions were low because the number of passengers waiting beyond the control point is comparable to the number of passengers detained at the control stop. The use of control is sensitive to passengers detained; therefore, for control to be effective, the number of boardings after control must be large enough to outweigh the disadvantage to those passengers detained.

The absolute and relative reductions were found to be dependent on the scheduled headway because better results occurred for smaller headways. This is probably due to increased probabilities of bunching under high-frequency conditions.

As the number of passengers using the route increased to a total of more than 60 passengers boarding and alighting, the wait-time reductions of headway-based control improved significantly (see Table 1). This is due to the increase in running time uncertainty from a greater number of boardings and alightings. It suggests that implementing headway-based control for uniform boarding profiles may be more feasible on routes containing large ridership populations.

A separate analysis was performed using Scenario 4 to determine the effect of changing the weight

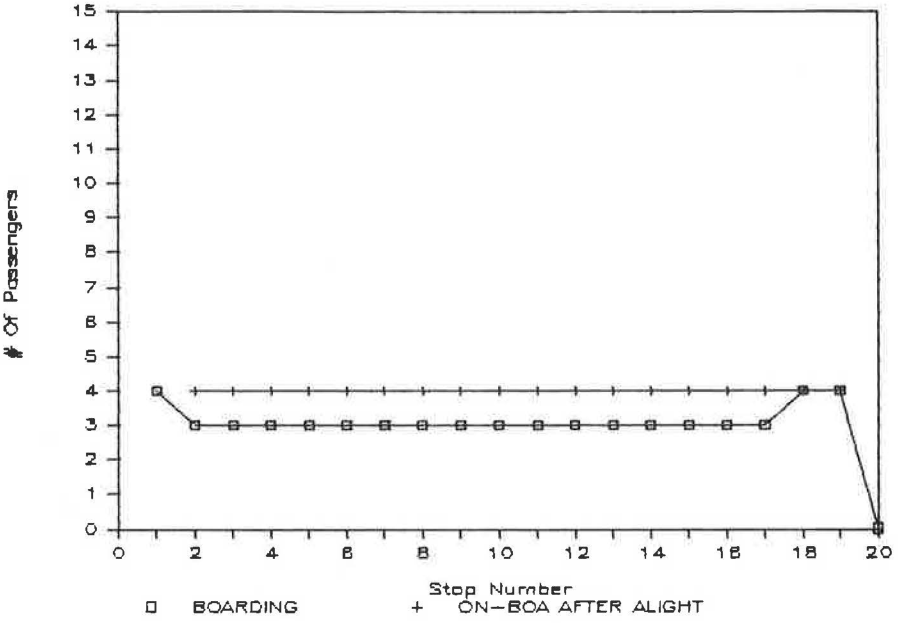

FIGURE 3 Effect of uniform boarding and alighting on headway-based control.

**TABLE 1 Effects of Increased Ridership on Headway-Based Control: Percentage of Reduction in Wait Time**

| No. of Passengers Along Route | Headway (min) | | | |
|---|---|---|---|---|
| | 4.00 | 6.00 | 8.00 | 10.00 |
| 60 | 1.00 | 0.49 | 0.07 | 0.00 |
| 120 | 1.59 | 0.97 | 0.45 | 0.08 |
| 240 | 2.71 | 1.93 | 1.22 | 0.71 |

assigned to delay to passengers detained at the control stop compared with passenger wait time downstream of control. It was found that the effectiveness of headway-based control decreases significantly as more importance is given to passengers on board at the control stop (see Figure 4).

Scenario 5 consisted of passengers boarding at the middle of a route and alighting at the end. This scenario produced the most significant reductions in passenger wait time when headway-based control is implemented. All of the passengers boarding were

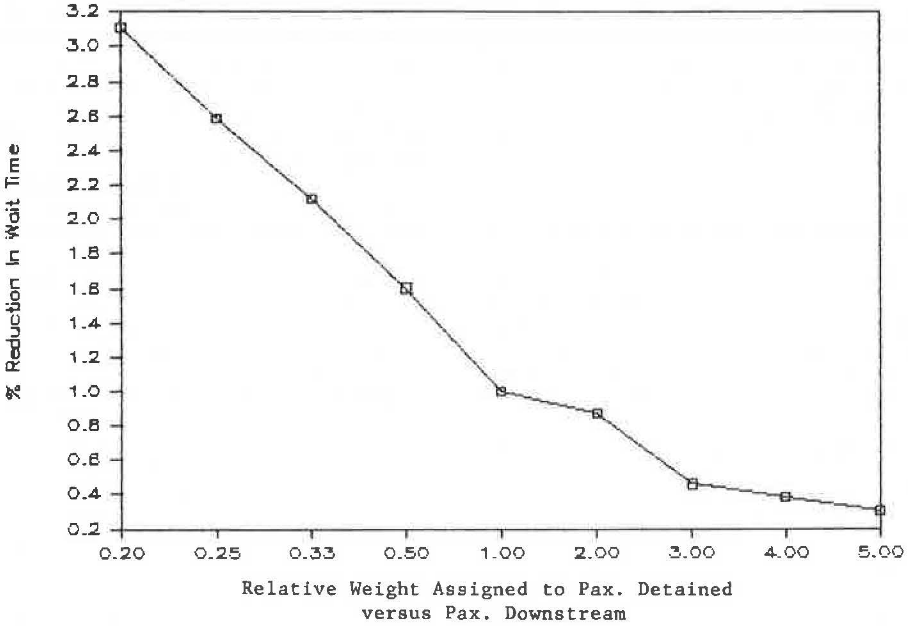

FIGURE 4 Effect of varying assigned weight of passengers detained at the control stop.

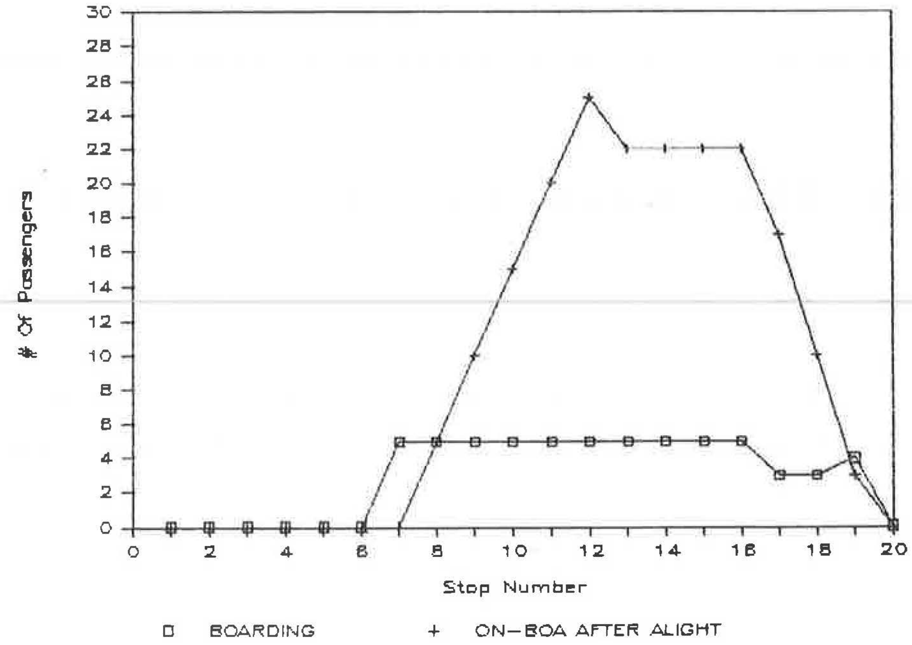

FIGURE 5 Impact of headway-based control for Scenario 5.

TABLE 2 Effects of Boarding Changes on Headway-Based Control

| Boarding Profiles[a] | Control Stop | Threshold (min) | Reduction (%) | Reduction (min) |
|---|---|---|---|---|
| Original data | 6 | 4.00 | 8.37 | 11.82 |
| 1 person at Stop 1; 4 people at Stop 7 | 6 | 4.00 | 5.40 | 7.61 |
| 2 people at Stop 1; 3 people at Stop 7 | 6 | 3.25 | 2.90 | 4.09 |
| 3 people at Stop 1; 2 people at Stop 7 | 6 | 2.75 | 1.98 | 2.79 |
| 4 people at Stop 1; 1 person at Stop 7 | 6 | 2.50 | 1.46 | 2.06 |
| 5 people at Stop 1; zero people at Stop 7 | 7 | 2.25 | 1.34 | 1.89 |

[a] Number of people boarding at each stop.

TABLE 3 Effect of Initial Headway Variation on Headway-Based Control

| Initial Headway Variation ($\text{min}^2$) | Reduction (%) | Reduction (min) |
|---|---|---|
| 1.42 | 8.37 | 11.82 |
| 1.59 | 9.13 | 13.04 |
| 1.77 | 9.90 | 14.30 |
| 1.96 | 10.67 | 15.60 |
| 2.15 | 11.45 | 16.93 |

downstream of the initial stops, allowing control to result in excellent wait-time savings to passengers with no delay to on-board passengers (see Figure 5; in this figure, headway = 4 min; control stop = 6; X = 4.00 min; and percent reduction = 8.37).

Because this profile produced the most meaningful results, a sensitivity analysis was conducted to evaluate the effect of more disaggregate changes to ridership profiles by assigning passenger boardings closer to the route origin. Modifications were made to the original boarding data of Scenario 5 (see Table 2), and the impact of headway-based control was reevaluated. By using scheduled headways of 4 min and moving one passenger from Stop 7 to Stop 1, the percentage of wait-time reduction decreased from 8.37 to 5.40. As more passengers were moved to Stop 1, the reduction in wait time for those downstream decreased and the threshold value, which affects those on board, also decreased. These results further substantiate that control strategies can incur significant savings when there is a small number of passengers on board at the control stop and when the majority of passengers board downstream of the control point.

Because the methodology discussed in this study assumes that buses are dispatched from the route origin on time and arrive at their initial stop with a low headway variation, a separate analysis was performed to evaluate the effects resulting from larger initial headway variation. The evaluation results presented in Table 3 indicate that increased headway variation associated with the initial stop along a route helps deteriorate route reliability and therefore enhances the benefits of implementing a control strategy.

Additional analyses using Scenario 5 data were performed to evaluate the effects resulting from changes in the percentage of on-street parking allowed between stops. With all other inputs held constant, including a 10-min headway and a distance between stops equal to 0.5 miles, the percentage of parking allowed on the link was increased from 10 to 90. It was found that increasing the percentage of parking allowed along a route also increases the percentage of passenger wait-time reduction using headway-based control (see Figure 6). As the percentage of parking along a route increases, headway variation also increases because the bus is being subjected to automobiles entering the flow from parking spaces, drivers opening doors into traffic, and space limitations associated with boarding and alighting of passengers. All of these factors con-

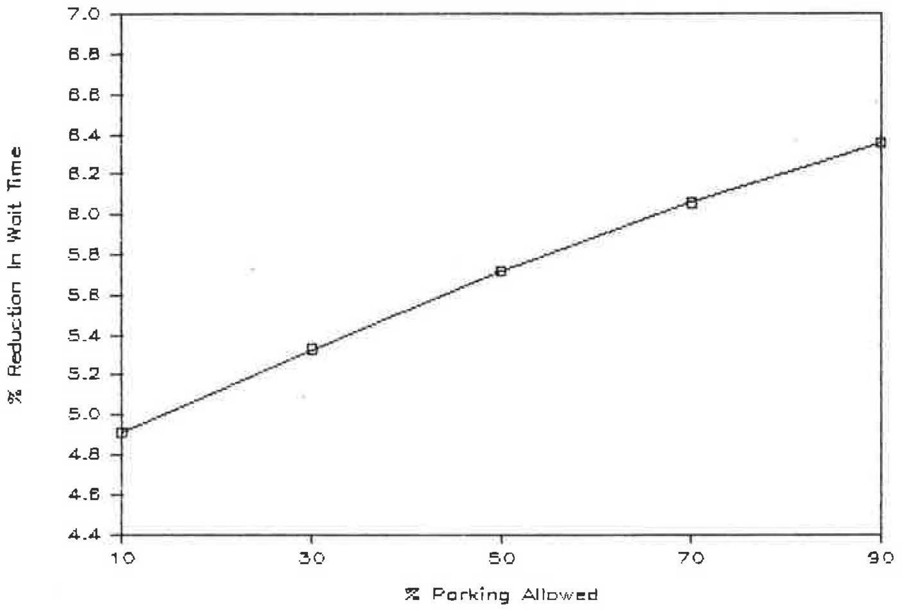

FIGURE 6 Effect of parking restrictions on headway-based control.

tribute to a deterioration of route reliability and thus an increase in passenger wait time. Therefore, the benefits of implementing headway-based control are enhanced by an increase in parking allowed along a route.

## CONCLUSIONS

Several findings can be reported from this research activity. Wait-time reduction effectuated by headway-based control is strongly influenced by the location of passenger boardings and alightings, total ridership on the route, scheduled headway, the relative weight assigned to passengers detained at the control stop, initial headway variation, and percentage of on-street parking permitted.

Profiles that consist of passengers boarding at the beginning of a route and alighting anywhere from the middle to the end produce little or no savings in wait time if headway-based control were to be implemented. Uniform boarding profiles exhibit marginal reductions in wait time unless the route ridership is large or the importance assigned to passengers detained at the control stop is less than the importance assigned to passengers waiting downstream of the control stop. The best results occur for profiles in which the number of passengers on board at early stops is low and thus the majority of passengers is boarding at the middle of the route and alighting at the end. Increases in the initial headway variation and amount of parking permitted help deteriorate route reliability, which enables headway-based control to be more effective. The significance of increasing the initial headway variation demonstrates the importance of dispatching vehicles from the route origin at regular intervals.

Collectively, the findings are intuitively appealing and suggest preferred conditions under which headway-based control is a viable operating strategy. The results can be used by transit managers and planners to identify candidate routes for headway-based control. The methodology described will be implemented shortly by a transit property in the northeast United States that is interested in responding to service reliability problems being experienced on several routes. In the course of that activity, the benefits of headway-based control will be evaluated relative to current route operating strategies.

## REFERENCE

1. M.D. Abkowitz and I. Engelstein. Methods for Maintaining Transit Service Regularity. In Transportation Research Record 961, TRB, National Research Council, Washington, D.C., 1984, pp. 1-8.

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