A Moving Vehicle Merging Control System

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•THREE research projects have been undertaken to design a system of optimal freeway control. The projects studied the John Lodge Freeway in Detroit, the Eisenhower Expressway in Chicago, and the Gulf Freeway in Houston. Each project has met with a certain degree of success, although each has developed a different control strategy. The one common factor among these projects is the concept that, in order to relieve freeway congestion, the rate of entry of vehicles from the entrance ramps has to be controlled in some manner.

The Houston project is the only one that assumed the secondary objective, apart from relieving freeway congestion, of aiding the ramp driver in performing the merging maneuver. This led to the development of the gap acceptance method of control. In this method, large gaps representing units of capacity are detected on the freeway lane adjacent to the on ramp, and vehicles are then released from the ramp in an attempt to fit them into the gaps. Since there would often be more vehicles trying to use the ramp than there are available gaps, it is necessary to delay vehicles on the ramp until a large enough gap becomes available. Stopping vehicles on the ramp also has an added advantage in that the travel time of a ramp vehicle from the stopped position to the merge point can be easily predicted (1), thus greatly simplifying the hardware designed to fit ramp vehicles into freeway gaps (2).

This form of control has been very successful in achieving both its primary objective of relieving freeway congestion and its secondary objective of aiding ramp drivers. Because of the primary objective, such controls have been operated only during peak hours when freeway congestion constitutes a problem. However, the secondary objective is thought to be of such importance that consideration was given to operating the controllers also during off-peak period when freeway capacity does not constitute a problem. Under such conditions there would likely be many more large gaps on the freeway than there are ramp vehicles to fill them. As a result many or perhaps even most ramp drivers would not experience a problem in finding an acceptable gap after they reach the merging area, and it would therefore be unnecessary to delay all vehicles on the ramp. Consequently, it was necessary to develop a gap acceptance controller that would not require all ramp vehicles to come to a stop. Such a control system has been designated a "moving vehicle merging control system" as opposed to the "stopped vehicle merging control system" described earlier.

THEORY

Model Description

A control system designed to fit ramp vehicles into freeway gaps has three basic requirements:

1. It must be able to measure or otherwise determine the estimated time-space trajectory of a ramp vehicle;
2. It must be able to measure and estimate the time-space trajectory of a freeway gap; and
3. It must be capable of controlling or affecting in a known manner at least one of the first two characteristics.

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The first two requirements are relatively simple because vehicle presence and speed can readily be detected with any of various types of sensors. For various reasons, it is more desirable to control the time-space trajectory of a ramp vehicle rather than that of a freeway vehicle. The stopped merge system controls the ramp vehicle by stopping all vehicles at a known point. In the first approach to the development of a moving merge control system, consideration was given to providing a changeable speed message sign on the ramp to meet the third requirement. The controller would then sense the presence and speed of a freeway gap, sense the presence and speed of a ramp vehicle, solve the equations of motion for the speed requirements of the ramp vehicle in order to match the gap, and then display this speed on the variable speed sign. The driver seeing the displayed speed would then have to adjust his speed accordingly in order to merge into the assigned gap. There are at least two serious objections to such a system: (a) in order to perform the control functions, freeway and ramp characteristics have to be sensed very far upstream of the merging area; and (b) it is doubtful that the average driver would react to the speed sign in the desired manner, if at all. The first objection would limit the application of the control system to very long ramps entering a freeway with no on or off ramps for a considerable distance upstream of the controlled entrance. The stability of the measured parameters would also be questionable over such a long distance. For reasonable distances the required speed changes would in some cases be too abrupt or of too large a magnitude. This approach was therefore abandoned for the one described next.

The freeway conditions under which the moving merge model would be applicable would connote numerous large gaps on the freeway. Many ramp vehicles would be able to enter these gaps without the aid of a control system and it would therefore be best if the control system does not affect them. Other ramp vehicles would not be so fortunate but would encounter a "block" on the freeway, making the merging maneuver quite difficult and forcing the driver to slow down or even stop. These then are the ramp vehicles that should be affected by control. Some of these vehicles can be matched with large gaps by a small adjustment in speed while others would require an unreasonably large speed adjustment. The latter group would therefore have to be stopped to await the arrival of an acceptable gap. Such a control system can be effected by a series of traffic signals on the ramp (Fig. 1). This system uses green and red "bands" that, through signal progression, lead into acceptable and unacceptable gaps on the freeway. Since vehicles that would otherwise be unable to match their paths with those of large gaps would be stopped by the first signal, the signal progression has to be designed for a stopped vehicle. It is therefore necessary to consider the equations of motion of a vehicle accelerating from a stopped position.

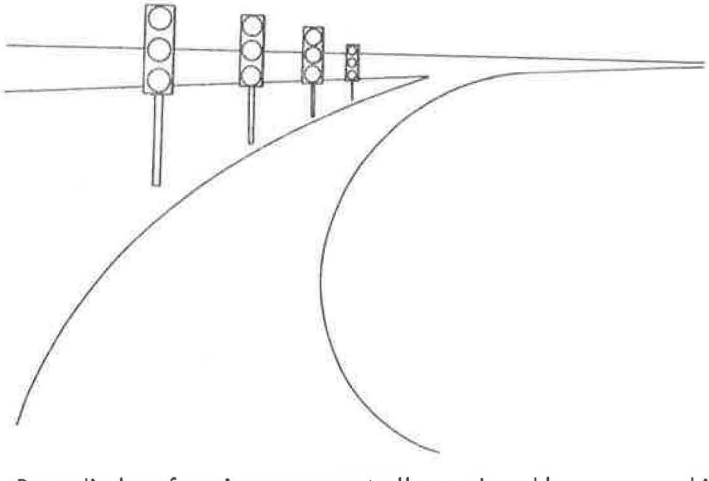

Figure 1. Ramp display of moving merge controller as viewed by an approaching driver.

Equations of Motion

The operation of the controller in terms of the proper instant in time to initiate a color band and the correct timing sequence through the signals depend entirely on the assumed traffic characteristics and the geometric layout of the freeway detectors and ramp signals.

It can be assumed that the acceleration of a vehicle is linearly related to its speed (1) as expressed by

$$\frac{du}{dt} = a - bu \tag{1}$$

where u is the speed of the vehicle, t is time, and a and b are constants.

This relationship leads to other vehicle operating characteristics that are determining factors in the operation of the controller. A ramp vehicle starting from a stopped position will therefore have the following characteristics. The time required to accelerate to speed u is given by

$$t = -b^{-1} \ln\left(\frac{a - bu}{a}\right) \tag{2}$$

Its speed after time t is given by

$$u = \frac{a}{b}\left(1 - e^{-bt}\right) \tag{3}$$

The distance covered in time t is given by

$$x = \frac{a}{b} t - \frac{a}{b^2}\left(1 - e^{-bt}\right) \tag{4}$$

The distance covered in accelerating to speed u is given by

$$x = b^{-1}\left[u + \frac{a}{b} \ln\left(\frac{a - bu}{a}\right)\right] \tag{5}$$

Given these relationships, the operating characteristics of ramp vehicles depend only on the assumed values of a and b, where a is the maximum acceleration used by drivers under "normal" conditions and b is the rate of change of acceleration with speed. These two parameters affect the projection time of gaps and the timing sequence of the signals. Their effect is treated in greater detail in another later paper (1). For purpose of illustration, it will be assumed that $a = 8$ ft/sec^2 and $b^{-1} = 18$ sec. It is desirable that the control equipment allow some flexibility in the assumptions regarding the values of these parameters.

The time-space trajectory of a vehicle that starts from a stopped position and uses normal acceleration as assumed is shown in Figure 2. The speeds reached at various traveled distances are also indicated.

Geometric Configuration

To provide drivers with a "follow the rabbit" type display, thus leading them into gaps, it would be desirable to have signals every few feet along the ramp and acceleration lane, starting far enough up the ramp so that even a standing vehicle can easily

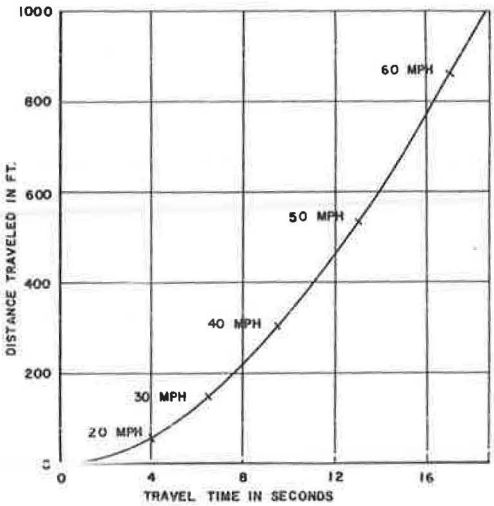

Figure 2. Time-space trajectory of a vehicle utilizing normal acceleration: $a = 8$ ft/sec^2, $b^{-1} = 18$ sec.

reach the highest anticipated freeway speed, and terminating at the end of the acceleration lane. Since the control system can never provide a 100 percent certainty that an acceptable gap will be available when the ramp vehicle gets to the merging area, the ramp display should not give the impression that it provides absolute right-of-way. The final decision of whether to merge or not must be left up to the driver. Furthermore, a vehicle that enters the signalized section of the ramp but travels too slowly will be stopped by one of the signals and will then have to accelerate from a standing start over a short distance before it has to merge. For these reasons, the last signal has to be placed some distance upstream of the ramp nose. In the prototype model described later, it was decided to place the last signal 150 ft from the nose. This also enhanced the adaptability of the controller to the stopped mode of control in which this last signal will act as the ramp control signal. The same controller could therefore operate on a 24-hour basis—operating in the stopped vehicle mode during peak hours and in the moving vehicle mode during off-peak periods.

The first signal encountered by a driver should be placed far enough from the nose so that a vehicle can reach the maximum desirable speed from a standing start. This distance is also limited by the ramp length. It is believed that there is little point in attempting to encourage a ramp vehicle to accelerate faster than 50 mph by the time it reaches the nose. It was therefore decided to place the first signal of this prototype installation 600 ft from the nose. Under the assumption made earlier, this would allow ramp speeds of approximately 52 mph at the nose (Fig. 2). This signal could, of course, be placed further from the nose if desired, as far as the length of the ramp will allow. Between the first and the last signal can be placed as many signals as desired. A great number of closely spaced signals would give drivers a better impression of the "follow the rabbit" type display. However, this somewhat unconventional display may create confusion especially to drivers trapped by a red band. It was therefore felt that the intermediate signals should be a sufficient distance apart so that a vehicle trapped in the signalized section could be given a leading green while still maintaining the basic sequence of signal indications.

The speeds of vehicles on the freeway as well as the size of the gap between them are measured by a single pair of closely spaced loop detectors placed in the outside lane of the freeway, some distance upstream of the ramp nose. The placement of these loop detectors will affect the projection time; this is discussed in another report (7).

Operation of Controller

The primary input to the moving merge controller is from a detection station on the freeway in the lane adjacent to the controlled entrance and some distance upstream of the merging area. At this detection station the controller measures freeway speeds and gaps between vehicles to determine whether the gaps are smaller or larger than a predetermined acceptable gap size, G. The controller is primarily concerned with changing the color indication on the first signal encountered by a ramp driver. The other signals on the ramp change in a consecutive sequence after the primary signal changes. This sequence may be predetermined or it may be established by the controller in accordance with the measured freeway speed. The action taken by the signal controller depends on whether the measured gap is greater or less than the acceptable

gap, G, and on the present state of the primary ramp signal, i.e., green, amber, or red. Henceforth, the amber shall be considered as part of the green phase. If the primary signal is green, the controller searches for gaps smaller than G. When such a gap is detected, a red band is initiated at the proper time. If the primary signal is red, the controller searches for gaps bigger than G, and when such a gap is found a green band is initiated at the proper time. The action to be taken by the controller is as follows:

State of Signal 1	Gap ≤ G	Gap ≥ G
Red	None	Turn signal green
Green	Turn signal red	None

The proper instant to change the primary signal indication is such that the travel time of the leader of the gap to the merging area is the same as that of a ramp vehicle stopped at the first ramp signal. This instant is designated the "decision point." The action just described is taken by the controller regardless of whether there is a vehicle waiting at the first signal or not.

The controller also receives indications from detectors placed on the ramp in front of each signal except the first signal. If one of these detectors indicates a vehicle trapped in the signalized section and thus stopped at one of the signals, the controller will modify the usual signal progression sequence by providing a leading green at this location.

It may be desirable to inform ramp drivers of the freeway speed in effect at the time in order to encourage them to accelerate to that speed. In this case, the controller can continually update the speed indication on a variable message speed sign placed on the ramp.

Projection Time

Every vehicle crossing the freeway detection station is projected for at least a short time. The term "projection time" as used here means the delay between the instant that a vehicle is first detected and the decision point.

The projection time depends essentially on (a) the location of the gap, (b) speed detectors, and (c) the travel time of a ramp vehicle, as determined by its location, the normal acceleration time to freeway speed, and the assumption that this speed is maintained until merging with the freeway. Under the assumption made earlier, the time required for a vehicle to accelerate to speed u is given by Eq. 2 as

$$t = -18 \ln \left(1 - \frac{u}{144}\right)$$

In accelerating to this speed, the driver would have covered a distance given by Eq. 5 as

$$x = -18 \left[u + 144 \ln \left(1 - \frac{u}{144}\right)\right]$$

If the first signal is located 600 ft upstream of the merge point, then the remaining distance to be covered is equal to 600 - x, which the driver is assumed to traverse at a steady speed of u. The travel time of a ramp vehicle from a stopped position in front of the first signal to the merge point is therefore given by

$$t = \frac{600}{u} + 18 + \left(\frac{2592}{u} - 18\right) \ln\left(1 - \frac{u}{144}\right) \tag{6}$$

where u is in ft/sec and t in seconds, $u \leq 52.5$ mph. Solving this equation for various values of u yields the times given in Table 1.

The freeway detector station has to be located a sufficient distance upstream of the ramp nose so that the travel time of a freeway vehicle, traveling at the highest speed anticipated, is equal to the ramp travel time given in Table 1, plus the largest gap to be measured, plus the starting delay of a ramp driver. The ramp vehicle should arrive in the merging area just shortly after the lead vehicle of an acceptable gap. If the green band is therefore set to lead into the merging area L seconds ahead of the lead vehicle, a ramp vehicle stopped at the first signal at the beginning of the green band should arrive in the merge area at a time equal to its starting delay minus L seconds after the lead vehicle. This lead time, L, shall be referred to as the leading green time. This would also be approximately true for a moving vehicle that just catches the beginning of the green band since the signal has to turn green while the vehicle is still some distance away so that it is not forced to slow down. The freeway detector should thus be placed so that the minimum freeway travel time between it and the nose equals the corresponding ramp travel time plus the maximum G plus L seconds.

The minimum distance that must be provided between the nose and the freeway detector is given in Table 2. To control ramp vehicles effectively when the freeway speeds are 60 mph, it is necessary that the freeway detectors be located at least 1750 ft upstream of the nose of the ramp. The projection time at various freeway speeds would therefore be given by

$$\frac{1750}{u} - (G + L) - \left[b^{-1} + \frac{600}{u} + b^{-1}\left(\frac{u}{ab} - 1\right) \ln\left(1 - \frac{ub}{a}\right)\right] \tag{7}$$

where u is in ft/sec.

Under the assumptions regarding a and b made earlier and assuming that (G + L) is set at 6 sec for all speeds, the relationship reduces to

$$\text{Projection time} = \frac{1150}{u} - 24\left(\frac{2592}{u} - 18\right) \ln\left(\frac{1 - u}{144}\right) \tag{8}$$

The timing operation of the controller is shown in Figure 3. To provide full flexibility as a research instrument, the only characteristic that should be considered fixed is the freeway travel time. All the other times should be adjustable by means of settings on a controller designed for research. This would enable adjustments not only

TABLE 1

RAMP TRAVEL TIME FOR VARIOUS FREEWAY AND RAMP SPEED CONDITIONS

Freeway Speed (mph)	Ramp Speed Reached (mph)	Ramp Travel Time (sec)
25	25	18.87
30	30	16.71
35	35	15.36
40	40	14.52
45	45	14.04
50	50	13.83
55	52	13.80
60	52	13.80

TABLE 2

MINIMUM DISTANCE REQUIRED BETWEEN RAMP NOSE AND FREEWAY DETECTOR

Freeway Speed (mph)	Required Freeway Travel Time (sec)	Freeway Detector Location (ft)
25	24.87	915
30	22.71	1000
40	20.52	1208
50	19.83	1458
55	19.80	1600
60	19.80	1748

for different acceptable gaps, at distinctive freeways speeds, but also for different ramp operating characteristics.

Upon turning the signals from green to red, the timing operation remains essentially the same. In this case, a leading red time is desired similar to the leading green time L. However, the operation of the controller could be such that the leading red time is equal to the leading green time. The projection time would therefore remain unchanged. Instead of turning the primary signal, it should remain amber at this point and turn red only after an extended amber period has expired. The other signals should turn red on schedule as if the first signal had turned red at the decision point, with the amber period inserted just prior to this time. In other words, the signals are turned red on the same timing sequence as they are turned green, except that the red on the primary signal is delayed by an amount equal to the additional amber time. It is thought that this procedure would encourage drivers who approach the signalized section just before a red band to speed up, thus still enabling them to enter the gap. An extended amber period is also desirable to prevent sudden stops.

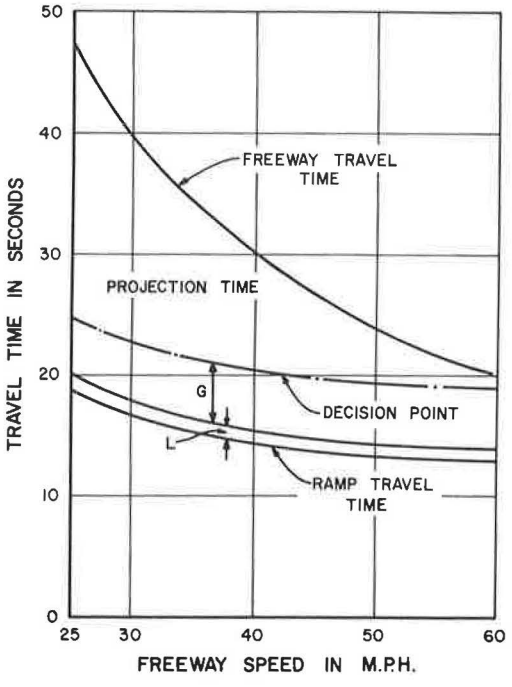

Figure 3. Controller timing operation.

Signal Sequence Timing

As explained earlier, the timing sequence at which consecutive signals change their color should be based on the time-space trajectory of a vehicle accelerating from a stopped position to the current freeway speed, utilizing normal acceleration, and then maintaining the freeway speed. The exact offsets will depend not only on the ramp vehicle characteristics but also on the placement and spacing of the signals. In more refined equipment, the offsets, especially that of the last signal, should change with freeway speed. However, in the experimental prototype described later, all that was required was an adjustable timing device by which the offsets could be set, since the freeway speeds could be controlled. The offsets required can easily be determined for any particular set of vehicle operating characteristics and signal locations with the aid of graphs such as Figure 2.

Figure 4 shows typical green and red bands for a freeway speed of 50 mph. It can be seen that only vehicles stopped at the first signal, or vehicles arriving just before the red phase, will be encouraged to change their speed. Vehicles arriving during the green phase may proceed through the controlled section undisturbed, which is desirable since they would have found the merging area empty anyway. The desirability of a curved time-space trajectory at the beginnning of the green band, as opposed to a straight-line (constant-speed) relationship, is evident since some vehicles may be stopped at the first signal. Furthermore, vehicles approaching the first signal near the beginning of the green band will only have to slow down without actually having to stop. The desirability of a curved time-space relationship at the beginning of the red band is shown by Figure 4. A vehicle entering the controlled section just before the red band at too slow a speed will be encouraged to speed up to the freeway speed. Otherwise, the slow vehicle will be stopped by one of the signals. However, in order to permit a vehicle traveling at 35 mph to maintain its speed and still enter the acceptable gap, the first signal should be delayed somewhat, resulting in a slightly different time-space trajectory for the red band than for the green band.

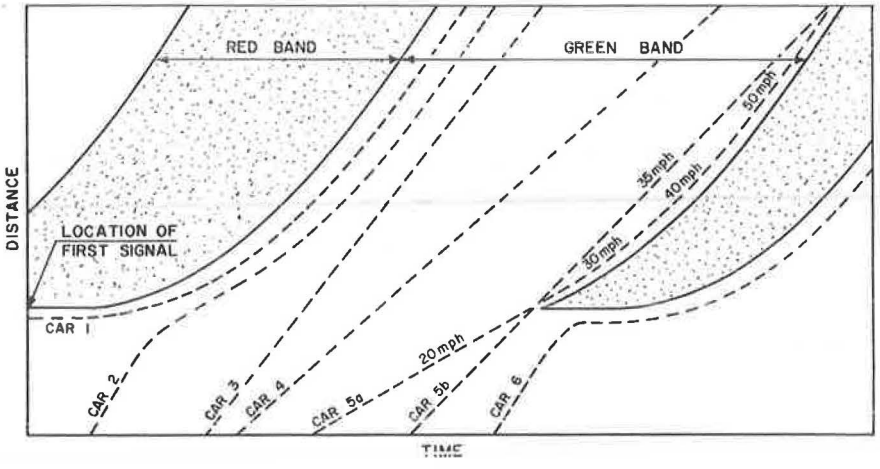

Figure 4. Illustration for 50-mph freeway speed.

TESTING

Test Facilities

To investigate the feasibility of the moving vehicle merging control system described, it was decided to test it in a controlled environment rather than under real-life conditions. For this purpose, a test track was laid out on the concrete runways of the Texas A&M Research Annex, formerly the Bryan Air Force Base (Fig. 5).

The test track consisted of three 12-ft lanes with a 12-ft shoulder on each side. The shoulders were sprayed with asphalt emulsion in order to create a more realistic freeway environment. An entrance ramp was located on a straight section of the simulated freeway. The entrance ramp, laid out with a 3-degree curve, was 14 ft wide and 600 ft long with an acceleration lane of 650 ft.

Control System

Four traffic signals were used in testing the moving merge model. The first signal was placed 600 ft from the nose and the others at 150-ft intervals so that the last signal was located 150 ft from the ramp nose. The signals were controlled by a standard fixed-time signal controller with the cams stacked to provide the desired timing sequence. An advisory speed sign was placed on the ramp 525 ft upstream of the nose, i.e., between the first two signals. The speed indication was changed manually. A radio communication system was obtained from the Bureau of Public Roads for communication with the ramp driver. This radio system has been successfully used in previous research. A receiver was placed in the ramp vehicles and prerecorded messages regarding the freeway speed were transmitted to the ramp driver.

Data were collected by 13 loop detectors taped to the pavement in front of each signal and at various locations on the freeway and acceleration lane. When a vehicle was detected it was recorded on a 20-pen event recorder, which permitted the correlation of ramp and freeway vehicle locations, ramp driver compliance to the controls, ramp vehicle travel time, the merge speed, and the exact location of any ramp vehicle that might have been stopped by one of the signals.

In addition, an instrumented vehicle was obtained on a loan basis from the Ford Motor Company. This instrumented vehicle allowed the measurement of physiological factors and vehicle control movements, such as fine steering reversals required for tracking, gross steering reversals required for lane changes and turning movements, acceleration reversals, brake applications, driver heartbeat rate, and galvanic skin response.

Experimental Design

In evaluating the feasibility of the moving merge concept, it must be recognized that all possible variables cannot be included in the investigation. A few of the variables must be selected for detailed study and the remainder must be assumed sufficiently random as to have no effect on the results and thus can be ignored. This approach restricts the extrapolation of the results to real-world behavior, but should indicate the ramp driver's acceptance of the controls imposed.

The variables chosen for study were divided into two groups: (a) those that were held constant and (b) those that were deliberately varied. The constant variables were ramp geometrics, condition of pavement, sex of driver, educational background of driver, and ramp vehicle characteristics. The experimental condition of the variables to be

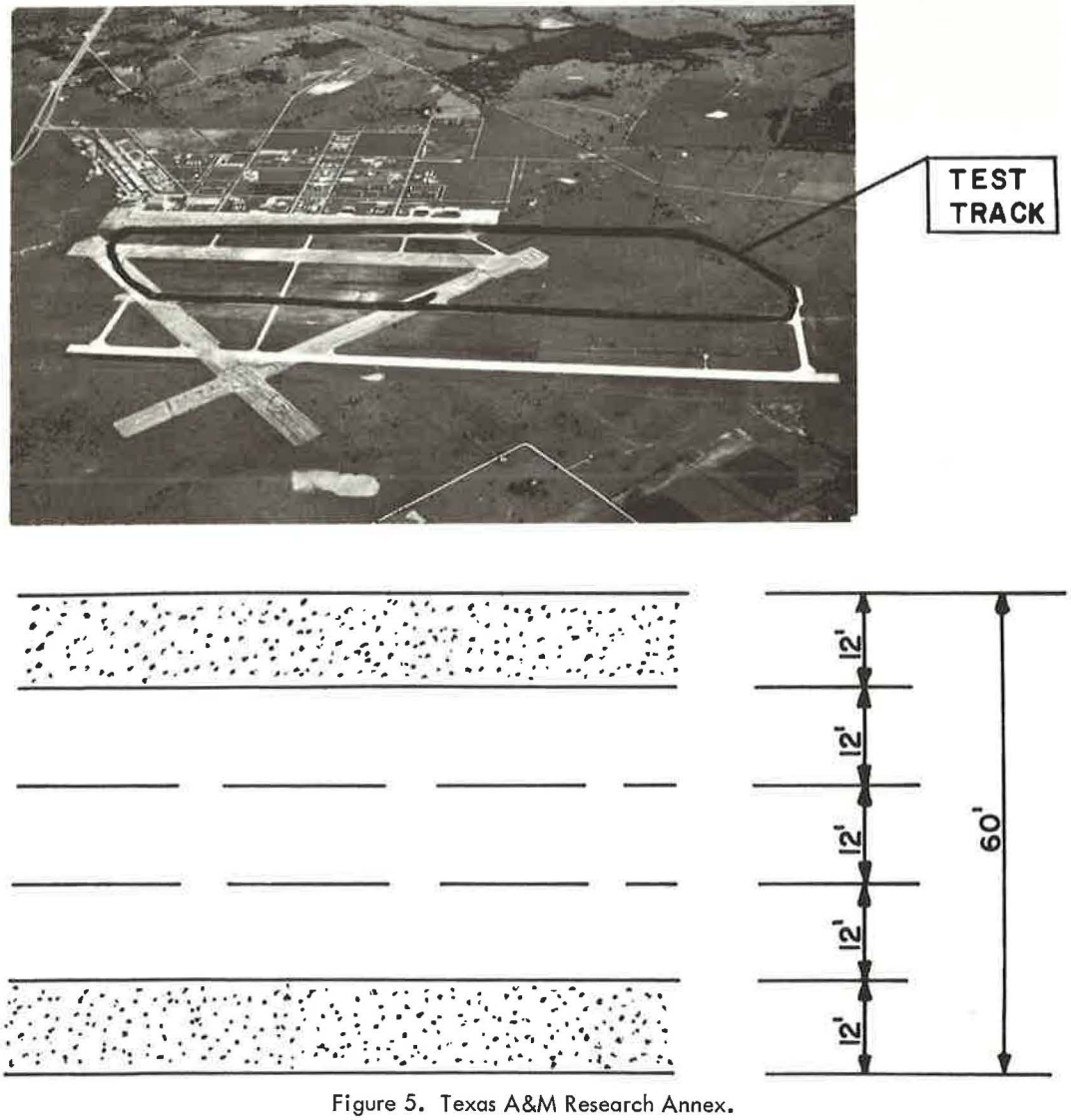

Figure 5. Texas A&M Research Annex.

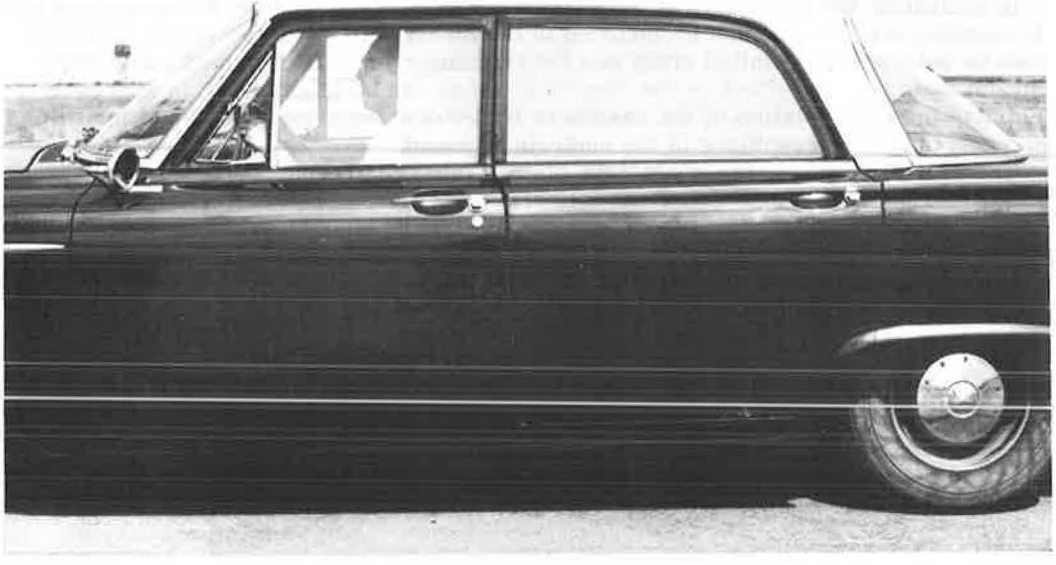

Figure 6. Ramp vehicle with blackout panels.

altered was established before developing the experimental design. These variables and their conditional levels are as follows:

1. Factor A—freeway speed: level 1, 40 mph; level 2, 50 mph; and level 3, 60 mph.
2. Factor B—ramp approach speed: level 1, 25 mph; level 2, 30 mph; and level 3, 35 mph.
3. Factor C—status of ramp signals as seen by driver approaching ramp (Fig. 4): level 1, signals not in operation; level 2, signals red, symbolizing a "block" on freeway, sequencing to green after pause; level 3, first signal green, balance sequencing to green, signifying approach at the start of the green band (Fig. 4); level 4, first and second signals green, balance sequencing to green representing an approach at the beginning of the green band; level 5, all signals green, depicting an arrival during the green phase; and level 6, first signal amber, balance sequencing to red, illustrating arrival at the beginning of the red band.
4. Factor D—advisory speed information to ramp driver concerning the freeway speed: level 1, none; level 2, visual presentation; level 3, audio presentation; and level 4, visual and audio presentation.
5. Factor E—backsight (no outside rearview mirror): level 1, ramp driver's vision unobscured; level 2, ramp driver's vision for estimating velocity and distance distorted by clear plastic panels with grid on the left side of vehicle; and level 3, ramp driver's vision obscured by blackout panels on the left side of the vehicle (Fig. 6).
6. Factor F—ramp drivers: level 1 to N, each level is represented by a different subject functioning as the ramp driver.

Each test run was evaluated on the basis of whether the ramp vehicle had been placed in a position to merge or not. This evaluation was utilized in both the first series with a standard automobile as the ramp vehicle, and in the second series with an instrumented car as the ramp vehicle. The physiological factors of heartbeat rate and galvanic skin response were obtained by using the instrumented car as the ramp vehicle.

Because of the large number of variables involved, the experimental design selected was a random balance design (3). This technique permits the screening of a large number of possible contibuting factors in an experiment involving a limited number of test runs. The results allow the factors of importance to be isolated for further study.

Table 3 gives the design matrix for the series of tests with the standard car. The elements of the matrix are determined with a random sampling process. All factors and levels are considered by choosing at random the level of each factor to be used in a particular treatment combination. The assumption can therefore be made that the interpretation of a factor is independent of every other interpretation made in the investigation.

It was recognized that the variation of driver characteristics would have to be taken into account. This was accomplished for the standard car by the random choice of drivers. In the series of tests involving the instrumented car, the ramp drivers were taken as factors with each individual considered as a conditional level.

TABLE 3

DESIGN MATRIX, STANDARD CAR SERIES

Test Run	Variable Levels				
	A	B	C	D	E
1	1	1	2	2	3
2	3	1	3	2	2
3	1	3	4	4	3
4	1	2	4	3	2
5	2	3	2	4	3
6	1	2	6	2	1
7	3	2	6	4	2
8	1	2	3	2	3
9	1	2	1	4	1
10	1	2	3	2	2
11	1	1	3	4	3
12	3	1	1	4	2
13	1	2	5	2	1
14	1	2	6	2	1
15	3	2	1	4	1
16	3	2	4	2	3
17	3	1	5	4	2
18	1	1	2	3	2
19	1	1	1	1	1
20	3	2	3	4	3
21	2	1	5	1	2
22	3	1	4	3	3
23	3	3	2	3	1
24	2	2	1	1	3
25	2	3	6	2	3
26	3	1	3	3	2
27	2	3	1	1	2
28	3	3	6	1	1
29	3	3	4	3	2
30	2	3	2	1	3
31	2	1	6	3	1
32	2	1	5	1	1
33	2	3	2	3	3
34	2	3	4	1	1
35	2	3	5	3	1
36	2	3	5	1	2

Experimentation

A sample of undergraduate students was selected as ramp drivers for the first series of tests. The subjects averaged 21 years of age with 5½ years of driving experience. All had taken a driver's education program while in high school.

The subjects were instructed to perform the merge operation in accordance with the conditions presented to them. The only specified condition was that the vehicle was to approach the ramp at a given speed for each test. Vision to the left-rear was varied through the application of special panels on the driver's side of the ramp vehicle (Fig. 6). Two methods were used to present the freeway speed to the ramp driver: (a) the freeway speed was displayed on a standard type highway speed sign, or (b) an audio message was transmitted through the induction radio system. The status of the ramp signals as seen by the ramp driver as he approached was accomplished by the manual operation of the signal controller. The signal sequence was initiated so as to lead the ramp vehicle into a fixed gap on the freeway.

A freeway gap of approximately 4 sec was chosen for all test runs. The lead vehicle on the freeway maintained the freeway speed at the velocity designated by the design matrix, and the lag vehicle was spaced accordingly.

Thirteen detectors were monitored on the ramp, acceleration lane, and outside freeway lane. Actuations of the loop detectors were recorded by a 20-pen recorder during each test run. Data reduced from this tape permitted the plotting of time-space diagrams of each merge (Fig. 7) as well as the evaluation of the merge and calculation of ramp accelerations and velocities.

The second series of tests involving an instrumented vehicle were performed with graduate students as ramp drivers. The average driver in this group was 26 years old with 12 years of driving experience. Only 25 percent had received formal driver education training in high school.

The additional data obtained, heartbeat and galvanic skin response, were recorded directly on magnetic tape in the instrumented vehicle. A special computer program was used to evaluate and print these data. The loop data tape was processed in the same manner as that of the first series.

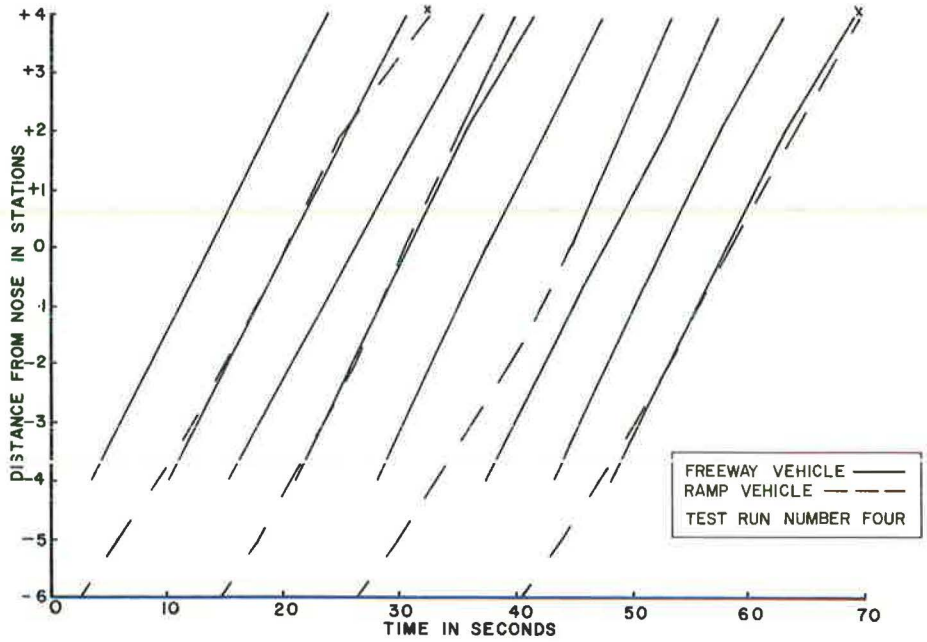

Figure 7. Time-space diagram—test run No. 4.

Automatic Controller

In the development of an automatic controller to perform the moving merge control function, work has proceeded on the modification of the first prototype merging controller developed on the Gulf Freeway Surveillance and Control Project (8). Since stopped merge control and moving merge control are similar in many respects, this modification was fairly easy to achieve. However, modification was completed too late for inclusion in this paper.

EVALUATION

Merging Maneuver

This investigation demonstrated that ramp vehicles can be place in position to merge with a moving vehicle merging control system (Fig. 8). However, having been placed in position, there was a great difference in the acceptance of the gap by the subjects. The more experienced drivers accepted the gap with higher frequency and with less use of the acceleration lane than those with less experience.

In the evaluation of each series of tests, values were assigned to the merge situations as follows:

1 Ramp vehicle in position to accept gap at the nose of the ramp;
0 Ramp vehicle not in position to accept gap at the nose of the ramp;
- Test run data disregarded as all levels of treatment combination were not correct.

The evaluation matrix for the standard car series is given in Table 4.

Included in the random balance design is the assumption that each factor can be considered individually. Therefore, linear statistical models can be assumed for each factor. The first series of tests had an additional effect in that each driver provided one observation for each treatment combination. Consequently, in the analysis of variance this replication must be taken into account.

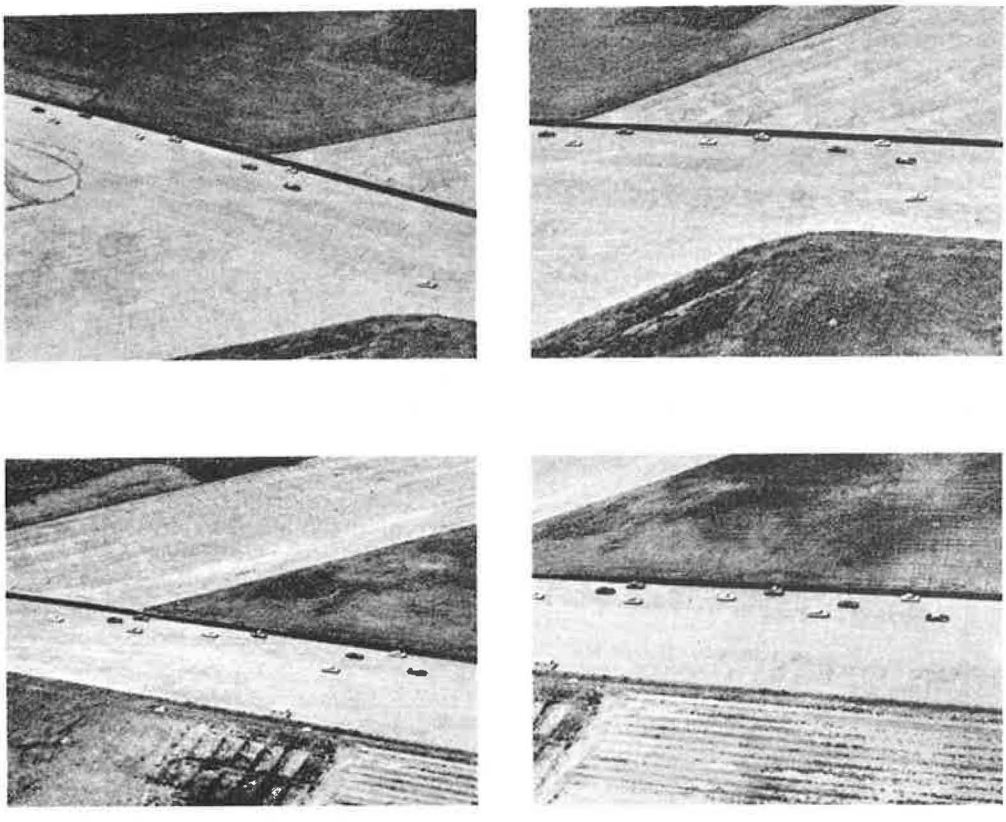

Figure 8. Time sequence.

The statistical model for the first series is represented by

$$Y_{ij} = m + r_i + f_j + e_{ij} \qquad i = 1,\ldots b \qquad j = 1,\ldots t$$

where

m = the true mean effect,
r_i = the true effect of the i th replication (driver),
f_j = the true effect of the j th factor, and
e_{ij} = the true effect of the experimental unit that is subject to the j th factor in the i th replication.

The analyses of variance for the factors that show a significant difference between levels are itemized in Table 5. This significance would lead one to conclude that these factors are important contributors to placing the ramp vehicle in a position to merge.

It should be noted that individual drivers are not a factor in the first series, but account for more variation than the factors being considered. Drivers as well as freeway speed, status of ramp signals as seen by the ramp driver, and backsight should be given further study.

To determine if bias had been created by the grouping of data, it was necessary that the effect of the factors within drivers be considered. Only Factor C, status of ramp signals as seen by the ramp driver, shows significance. This indicates that the effect of signals differs among the drivers, which is to be expected. Table 6 presents the analysis of variance for this factor.

TABLE 4

EVALUATION MATRIX, STANDARD CAR SERIES

Test Run	Driver			
	1	2	3	4
1	1	1	1	0
2	1	1	1	0
3	1	1	1	1
4	1	1	1	0
5	1	1	1	1
6	1	1	1	1
7	1	1	1	1
8	0	1	1	0
9	-	-	1	-
10	1	0	1	0
11	1	1	1	1
12	-	1	0	0
13	-	1	1	-
14	1	1	1	1
15	0	1	1	-
16	1	0	-	0
17	0	1	1	0
18	1	1	1	1
19	1	1	1	0
20	1	0	-	1
21	0	1	1	-
22	0	1	-	0
23	0	-	1	0
24	1	1	0	-
25	1	1	1	1
26	0	-	-	0
27	1	1	1	0
28	1	1	1	-
29	0	-	-	-
30	1	1	1	0
31	1	1	1	-
32	0	0	0	0
33	-	1	1	1
34	0	-	0	0
35	0	1	1	0
36	1	1	1	0

TABLE 5

ANALYSIS OF VARIANCE, FIRST SERIES

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Ratio
Total	117	25.78		
Drivers	3	5.16	1.72	10.13[a]
A	2	1.59	0.79	4.67[b]
Error	112	19.03	0.17	
Drivers	3	5.16	1.72	10.54[a]
C	5	3.82	0.76	4.67[b]
Error	109	20.23	0.16	
Drivers	3	5.16	1.72	9.47[a]
E	2	1.27	0.63	3.48[b]
Error	112	20.35	0.18	

[a]Significant at the 1 percent level.
[b]Significant at the 5 percent level.

TABLE 6

ANALYSIS OF VARIANCE, FIRST SERIES GROUPING

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Ratio
Total	117	25.78		
Drivers	3	5.16	1.72	5.57[a]
C within drivers	20	6.18	0.31	1.88[b]
Error	94	15.43	0.16	

[a]Significant at 1 percent level.
[b]Significant at 5 percent level.

In the second series of tests, with the change of variables, there was no indication of significance between levels of any variables considered; that is, even the difference between drivers was not sufficient to be other than a random difference.

Driver Stress

The time required for the ramp vehicle to approach, proceed up the ramp, and merge was less than a minute. Due to the delay in the galvanic skin response to a given situation, it was decided that this time was too short to provide any meaningful data. Thus the heartbeat rate was taken as a better variable to use in determining driver stress. An example of a driver's pulse rate during a test run is shown in Figure 9.

A significant change in the heartbeat rate is considered to have occurred when there is an increase or decrease of 10 beats per minute. Because the primary interest is stress, only changes above the normal rate are taken into account. Defining each time the driver's rate exceeds the point of significant change as a "stress-time", an index of driver comfort can be obtained. Table 7 is the stress-time matrix obtained from the second series of tests.

The heartbeat rate for each subject was taken for a full minute before and after his test runs. The mean of these observations was accepted as the normal rate for that driver.

The only factor that exhibited a significant difference between levels was Factor F (drivers). This significance is an indication that an additional study should be made in the area of driver stress in dynamic traffic situations. Table 8 is the analysis of variance for this factor.

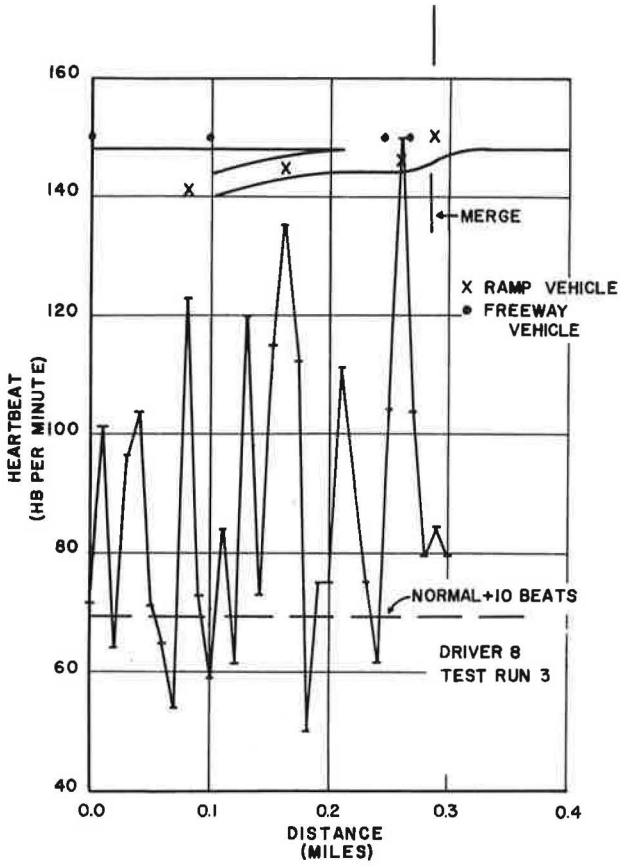

Figure 9. Typical driver's pulse rate during test run.

TABLE 7

STRESS-TIME MATRIX, INSTRUMENTED VEHICLE SERIES

Driver	Test Run					
	1	2	3	4	5	6
1	4	4	2	5	16	6
2	8	7	8	7	13	9
3	7	2	8	3	4	2
4		11	10	7	8	10
5	9	12	6	8	7	7
6	9	3	3	5	12	4
7	12	6	8	12	10	4
8	13	12	21	17	15	15

TABLE 8

ANALYSIS VARIANCE, SECOND SERIES

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Ratio
Total	47	804.48		
Drivers	7	526.65	75.24	10.83[a]
Error	40	277.83	6.95	

[a]Significant at the 1 percent level.

CONCLUSIONS

The feasibility of the controlled moving merge was confirmed by both series of this study. The first series of tests placed the ramp driver in a position to merge 70 percent of the time. The instrumented car series was successful more than 50 percent of the time.

These tests have demonstrated that the controlled moving merge can be accomplished successfully and safely. The factors of backsight, driver, freeway speed, and ramp

signals have been determined to be sufficiently important to warrant further research. The installation of a moving vehicle merging control system on a freeway would provide the opportunity for more detailed investigation as well as permit the study of the system under real-world conditions.

Subsequent research should also take into account principles of operation of a moving merge control system. It would appear necessary to determine under what conditions a controller should cease to function in the stopped vehicle merging control system and change to the moving vehicle system or vice versa. Some criteria should be developed for the determination of the benefits of 24-hour ramp control.

The second test series indicates that stress-time can be used as a factor in the indexing of driver comfort. If this approach to the evaluation of the level of service is to be accepted, further research into this area is required.

It is questionable as to the amount of driver stress desirable. Minimization of this stress might endanger the driver by reducing his level of alertness. These are some of the basic problems that should be considered in the future.

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