Design of Freeway Entrance Ramp Merging Control Systems

JOHANN H. BUHR, WILLIAM R. McCASLAND, JAMES D. CARVELL, and DONALD R. DREW, Texas Transportation Institute, Texas A&M University

The central concept in the control of a freeway system is the control of each individual entrance ramp. This report deals with the control of individual entrance ramps—in particular, with the design and installation requirements of a gap acceptance merging control system. The operation of such a controller and the detection and display requirements are discussed in in sufficient detail to allow the writing of functional specifications and the design of a merging control system.

•IN March of 1966, the first prototype automatic traffic-responsive merging controller was installed on the Telephone Road inbound entrance ramp of the Gulf Freeway in Houston. Since then, considerable experience has been gained in the operation of this instrument and in the prediction of its effects on traffic behavior. The prototype controller has led to the development of eight first-generation controllers that have been installed on the inbound entrance ramps of the Gulf Freeway. These controllers are basically of two types—demand-capacity controllers and gap acceptance controllers. Although certain restrictive site characteristics and traffic-flow conditions may dictate the use of a demand-capacity controller, the gap acceptance controller is generally more desirable. Under contract with the Bureau of Public Roads, the Texas Transportation Institute has developed functional and operational specifications for gap acceptance control systems, some of which are discussed in this paper. Based on these specifications, three new second-generation controllers are presently under construction.

Because sufficiently detailed documentation has lagged far behind the rapid development of merging control systems, much of the associated technology is limited to relatively few researchers. The purpose of this paper is to narrow the gap between technology and documentation. It is hoped that it will enable the traffic engineer to write the functional specifications and design the installation of a merging control system suited to his own requirements.

THE CONTROL FUNCTION

Basically, the function of a freeway control system can be qualitatively stated as consisting of two objectives: (a) the optimization of freeway operation and (b) the optimal use of freeway gaps by merging ramp vehicles. Pursuant to these objectives, a multilevel design approach has been introduced as a means of decomposing the control function for a rational development of a freeway control system (1). This multilevel concept is directed toward establishing a hierarchy of levels of control, partly based on varying degrees of sophistication. The four suggested levels in ascending order of sophistication are the regulating, the optimizing, the adaptive, and the self-organizing control functions. This paper is concerned with controllers of up to the second, or

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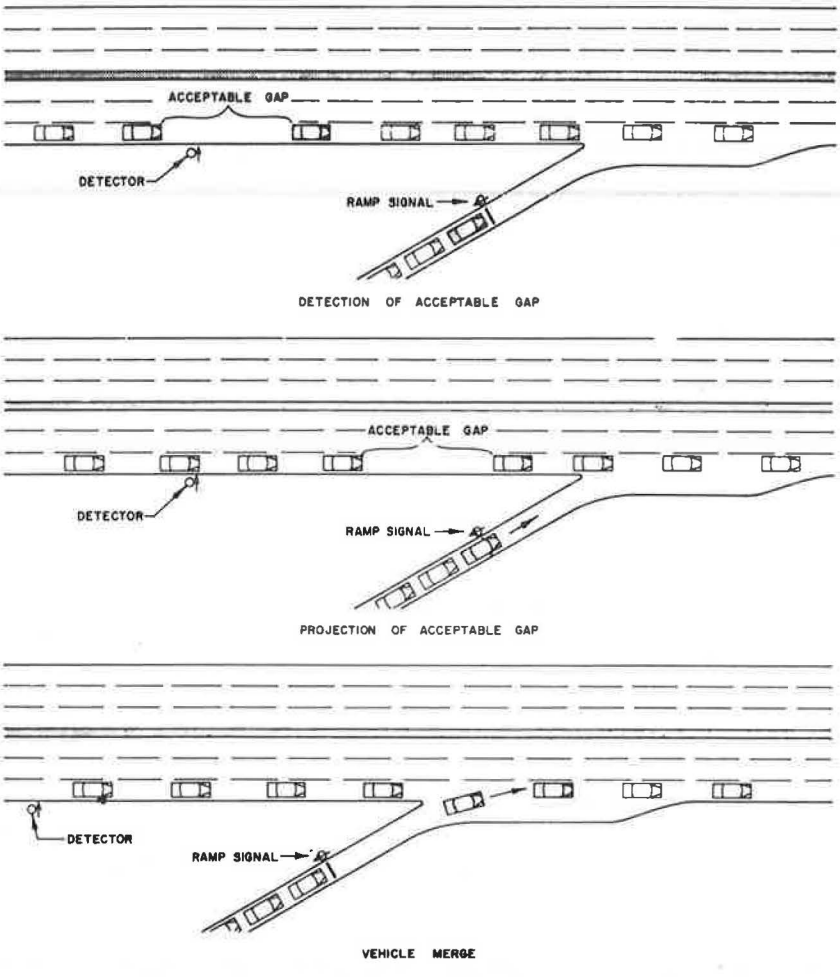

Figure 1. The three steps of entrance ramp control.

optimizing, level of control. Each controller operates an "isolated" merging area, or subsystem, without interconnecting or regard for the operation in other subsystems.

The gap acceptance concept is the basic or central principle of the multilevel control scheme. The higher levels of control exert their influence on the traffic process by modifying the basic control parameters, i.e., the service gap (2). Gap acceptance control is achieved by a controller that measures gaps and speeds in the outside freeway lane while a vehicle desiring to enter the freeway is stopped at a traffic signal on the ramp. When a gap large enough for the ramp driver to enter is found, the ramp vehicle is released by turning the signal indication to green at the proper instant so that the ramp vehicle will reach the merging area at the same time as the moving gap. This procedure, shown in Figure 1, can be thought of as consisting of three steps: gap detection, gap projection, and gap acceptance.

OPERATION OF CONTROLLER

To achieve the operation described, the controller must be able to measure the time headways between vehicles at a location upstream from the merging area to the extent that it can determine if a certain gap is larger or smaller than a predetermined gap. Furthermore, it must have the capability of measuring the speed of vehicles on the out-

side lane of the freeway, the capability of changing the indication of a ramp display such as a traffic signal, and the capability of determining through gap projection based on the speed measured the correct moment to change the signal indication. Each of these functions is discussed in greater detail later in this paper. These are the basic functions of the gap acceptance controller. However, to operate in a real-life environment, the controller must have a number of other auxiliary functions, the first of which is concerned with the operation of the ramp signal.

Operation of Ramp Signal

Assuming that the ramp signal is a conventional green-amber-red traffic signal, there are three ways that it can be operated: (a) the signal gives a green indication at the proper time whether or not there is a vehicle waiting; (b) the signal normally rests on green when there are no vehicles waiting; or (c) the signal normally rests on red when there are no vehicles waiting.

If, under the first alternative, a platoon of vehicles approaches the ramp signal, which is green but turns red just before the arrival of the lead vehicle, a hazardous condition will be created by an instrument designed to enhance safety. This operation has been observed in practice on several occasions and is deemed quite undesirable. It is therefore necessary to have a detector, the check-in detector, located immediately upstream from the signal in order that the controller might recognize the presence of a vehicle waiting at the signal.

The second alternative has been suggested to guard against failure of the check-in detector to indicate the presence of a waiting vehicle, either by virtue of detector failure or incorrect location of the sensor. This alternative means that only if a vehicle arrives should the signal turn red to stop the vehicle, and then it releases the vehicle in the normal manner. This operation is conceptually unappealing. Not only will it create the same hazardous conditions as the first alternative but it will also let many vehicles pass the signal uncontrolled unless an additional upstream detector is used, thus making the control system more complex than necessary.

The third alternative, with the signal resting on red and the controller providing a green signal only if there is actually a vehicle waiting, is the most desirable and is being used on the Gulf Freeway. This requires the use of a check-in detector, failure of which can be guarded against as mentioned later.

To turn the signal back to red after a vehicle has been released, a check-out detector, placed immediately downstream from the signal, was used at first on the Gulf Freeway. The signal was turned to red as soon as the released vehicle actuated this detector. Although conceptually appealing, problems were caused by the variability in the distance from the signal at which ramp drivers stopped (3). Sometimes a vehicle will stop with its front wheels past the signal, actuating the check-out detector, and, if the check-out detector is moved further downstream, two-vehicle platoons will often pass the signal. It was found far more desirable to turn the signal back to red, based on fixed lengths of green and amber phases, without using a check-out detector (3). As noted later in this paper, however, such a detector is required for the detection of slow vehicles. It also forms part of the detection system for the real-time evaluation of freeway operation (4).

Control Overrides

Based on the regulating function as described, the control system should theoretically operate adequately under all conditions. However, in a real-life installation, there are three extraneous conditions that will affect this operation: (a) vehicles stopping in the merge area, (b) ramp queues backing into other traffic systems, and (c) excessively long red phases. The effect of these three possible occurrences can be minimized by special override features that tend to maintain the desired operation, and, if the operation fails, they tend to return the control to the desired mode of operation.

There are a number of conditions that can cause drivers to stop in the merging area. When this happens, releasing another vehicle will simply compound the problem because the released vehicle will also be forced to stop and wait for an even bigger gap

for which, in turn, another vehicle would have been released. It is therefore necessary to hold the ramp signal on red or to increase the service gap considerably until the merge area has been cleared. The occurrence of this situation should be detected with a presence detector—the merge detector placed in the merge area.

Furthermore, the ramp may be so located that an excessively long queue at the ramp signal will back into an intersection of the frontage road with a cross-street, thus adversely influencing an adjacent traffic system. To minimize this interference with off-freeway traffic systems, it is necessary to detect such an occurrence with a suitably placed presence detector (the queue detector), which, if continuously occupied for longer than a certain period, will cause vehicles to be metered at a somewhat faster rate by reducing the service gap. At locations where the ramp demand is fairly low and/or there is ample storage space for queues, this feature may not be necessary.

If a vehicle is delayed at the signal for longer than a certain period, the driver will probably assume that the signal is out of order and proceed past the signal, violating the control. This period varies among drivers, but is considerably shorter than at a traffic signal on a regular surface street intersection probably because of the somewhat unconventional location of the signal and the absence of any immediate danger in violating the signal. More often than not the violating driver is forced to stop in the merge area. It is therefore necessary to have a maximum red phase, insuring that the signal will turn green at least once every so often. In practice, on the Gulf Freeway, a 20-second maximum waiting time is used. When a vehicle has occupied the check-in detector for longer than 20 seconds, it is given a green signal regardless of the availability of gaps. However, it is considered more desirable to reduce the service gap gradually as the waiting time at the signal increases (5). Furthermore, this feature should be based on the length of red phase rather than the occupancy of the check-in detector. This would protect the control against failure of the input detector to sense the presence of certain types of vehicles, such as motorcycles or high trucks.

These functions, considered as overrides or optimizing functions in the multilevel control approach, affect control by modifying the service gap given by the regulating function (5).

Trucks and Slow Vehicles

At locations where a relatively high percentage of the ramp traffic consists of trucks, it may be desirable to make special allowances for this type of vehicle. These allowances can be either releasing a truck for a bigger gap than a regular passenger vehicle or providing a longer ramp travel time by turning the signal green earlier, or both (3). This would require some specialized detection equipment to sense the presence of a truck at the signal. However, since the performance of some trucks, especially when empty, may approach that of regular passenger cars, it may be necessary to sense the weight/horsepower ratio of vehicles waiting at the signal. It is doubtful that this feature can be made cost-effective.

A better way of handling slow vehicles is to provide for the detection of vehicles at a point between the ramp signal and the merge detector. The travel time of a released vehicle from the signal to this detector can then be measured, and, if greater than a predetermined value, the signal can be held on red, or the service gap increased until the vehicle has cleared the merge detector or until the merge detector overrides the operation.

Multi-Vehicle Metering

When the ramp signal turns green, it stays green for a fixed period long enough to release a single vehicle. The signal then turns amber (where allowed by state law, it may be desirable to omit the amber phase) for a short fixed period and then turns back to red. It is necessary that it stay red at least long enough to give the second vehicle in line time to pull up to the signal. This minimum cycle length should be about 5 sec but not less than 4 sec. As a result, the maximum number of vehicles that can be metered under ideal conditions is approximately 720 per hour. When ramp demand approaches this value and there are many large gaps available on the freeway, it is

desirable to employ some form of multi-vehicle metering that permits more than one vehicle to pass the signal on the same green phase.

Multi-vehicle metering has not been tested extensively on the Gulf Freeway, but some experiments are now being planned. One experiment simply involves the use of longer fixed-time green phases, designed to let two-vehicle units or three-vehicle units pass the signal in one phase. The other experiment involves an additional display, to be used in conjunction with longer green phases that would indicate the number of vehicles that should proceed down the ramp. If multi-vehicle metering is planned, the controller should have the additional capabilities of recognizing gaps larger than several predetermined values and of providing several green phase lengths and perhaps amber phase lengths. The use of multi-vehicle metering will also affect the location of the gap detector, as discussed later.

Service Gap

The service gap is defined as the smallest gap for which the controller will release a vehicle. Unless one of the previously discussed overrides is in operation, this gap would normally not be smaller than the "acceptable" gap of ramp vehicles. The service gap should increase as the freeway speed decreases (2, 6). Once the freeway reverts to forced flow conditions and speeds drop below 20 mph, the service gap should be sharply increased, because even a small space between vehicles constitutes a large time headway. For example, if the freeway should come to a complete stop, the gap over the gap detector will look like an infinitely large gap, and the controller will accordingly release many vehicles off the ramp unless it is designed to handle such an eventuality. In the local controllers presently being used, the regulating function was such that, if the speed dropped below a preset value, vehicles were metered at a fixed rate. This critical speed was based simply on the subjective evaluating of the day-to-day operation of the freeway and was usually set at about 25 mph. It was felt that under forced-flow conditions there was little need for projecting gaps, since they would probably be so unstable as to make it impossible to fit vehicles into specific gaps. On the other hand, according to the latest thinking, it may still be preferable, even under these conditions, to attempt to fit vehicles into specific gaps that represent, in effect, units of capacity. Even if the time-space trajectories and the vehicle and the gap are not matched exactly, the unit of capacity will still be in the vicinity of the merging area to absorb the unit of demand. The function defining the gap size as based on freeway speed is presented in another report (5).

Apart from the functional requirements already discussed, the controller should have the capability of determining the size of the service gap, based on the speed measured on the freeway. In the existing local controllers, this is achieved by four level monitors, defining five speed ranges. The speed ranges can be defined by adjustable dials. When speeds are in the lower range, the controllers operate on a fixed-time basis. For each of the other four speed ranges a service gap can be set by adjustable dials. In this manner, the continuous service-gap speed-function can be approached by a four-step function. This appears to be a satisfactory manner of determining the service gap, although use of the continuous function would be more desirable.

DETECTION REQUIREMENTS

Number of Detectors

Figure 2 shows the functional components of the typical merging control system. As shown in the figure and as discussed, there are five detectors involved: the gap/speed detector (D_A), the check-in detector (D_i), the merge detector (D_m), the queue detector (D_q), and the slow-vehicle detector (D_t). All of these detectors would normally be used, but, as mentioned earlier, the queue detector may not be required at certain locations. Furthermore, the designer may decide not to use the slow-vehicle functioning, consequently omitting D_t. It should be kept in mind, however, that for system control of the freeway this detector doubles as a counting detector and is therefore quite important. The other detectors on the ramp are all presence detectors that cover a large area and are unsuitable for counting purposes.

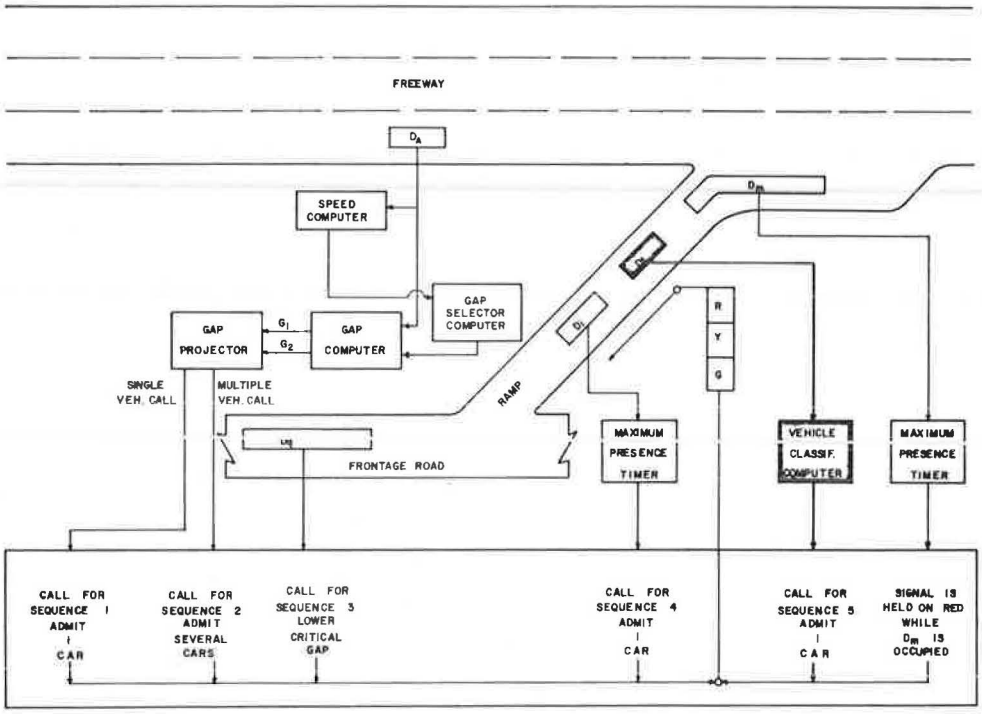

Figure 2. Functional components of the typical merging control system.

The detection of gaps and speeds can be accomplished with a single detector. However, since the speed is also used for estimating the arrival time of a gap in the merging area, the speed must be measured quite accurately. To achieve the desired accuracy, a set of two closely spaced detectors must be used at his location. Depending on the local requirements, therefore, the number of detectors used with a merging control system can vary between three and six.

Size and Location of Detectors

The size and location of a detector and the behavior of a driver are critical factors to be considered before most detectors can be expected to perform their intended functions. The intended function of the check-in detector is to indicate the presence of a vehicle at the signal. If a vehicle does not stop over this detector, the signal will remain red until the maximum red phase override is called in. The result of such a situation is the formation of long queues and the creation of long delays in the system. Studies indicate, however, that if the detector were of a minimum size of 10 ft long and 6 ft wide and no further than 5 ft from the signal, this situation would be all but eliminated (3). These are minimum dimensions. Larger values would be more desirable.

The size and location of the merge detection area also depend on driver behavior, which is largely influenced by the geometric design of the ramp and acceleration lane. Ideally, the merge detector should sense all vehicles stopped in the merging area. However, in practice, the position at which drivers stop was found to be so variable that even quite a large detection area fails to detect all stopped vehicles. Some drivers will stop 50 ft or more upstream from the ramp nose, while others will travel right down to the end of the acceleration lane. The latter type of operation does not constitute much of a problem because as long as a vehicle does not block entry to the freeway, the need for holding the signal on red is decreased. The best location of the merge detector can be fairly well established by observing the operation of an entrance ramp

during a peak hour. In general, the detection area should stretch from some distance upstream from the ramp nose to about 40 ft downstream from the ramp nose.

The queue detector would normally be located on the frontage road. Its location depends entirely upon the geometric layout. In general, it should be located no closer than about 4 or 5 vehicle lengths from the traffic system that it is designed to protect. Its size should be so that the detection would not drop out between vehicles in a slowly moving queue—i.e., the next vehicle should normally enter the detection area before the previous one leaves it. This requires a length of at least 12 ft. However, if it is desired that the queue detector double as a counting detector for counting frontage road traffic, a point sensor can be used. In this case, however, the controller should have the additional capability of, in effect, extending the size of the queue detection area by a delay function. Such a function would hold a call from the sensor for a predetermined period after a vehicle leaves the detection area.

The purpose of the slow-vehicle detector, D_t, is to determine if a ramp driver's travel time, from the instant the signal turns green to the instant the vehicle actuates D_t, exceeds a predetermined value. When this happens, the controller should hold the signal on red until the merge override can be called in. The reason for using this function is that the merge detector is usually located so far from the signal that, by the time the merge override is called in, a second vehicle will often have been released. This second vehicle is then also forced to stop, perhaps in advance of the merge detector. When the first vehicle then leaves, the average override drops out and a third vehicle is released while the second is still stopped in the merge area. The controller can have some difficulty in recovering from this situation. D_t therefore allows the prediction of a stop in the merging area and tends to avoid the situation of two vehicles stopped in the merge area. As such, it is a highly desirable feature of the system.

To perform its intended function properly, D_t must be located so that a ramp vehicle, using the correct acceleration to hit the gap, would actuate it within a time interval representing the minimum signal cycle length. Furthermore, it is necessary that this sensor distinguish between separate vehicles. It therefore has to be a point sensor longitudinally and cover a lateral width of at least 6 ft. The location of D_t with respect to the signal thus depends on ramp-vehicle operating characteristics (3). When this feature is used, it may be desirable to have a cutoff period because sometimes a driver will miss his green signal and not proceed down the ramp. This would cause the slow-vehicle feature to be called in when there is actually no vehicle on the ramp. However, since the slow-vehicle feature has a built-in cutoff period, a special cutoff feature will be of value only with certain limited geometric layouts.

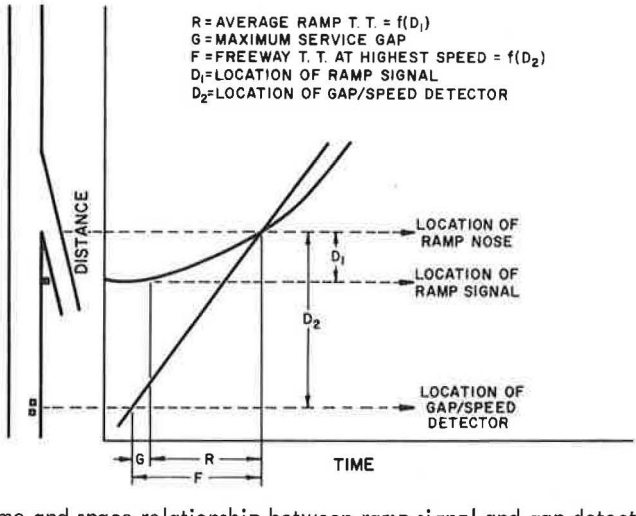

Figure 3. Time and space relationship between ramp signal and gap detector locations.

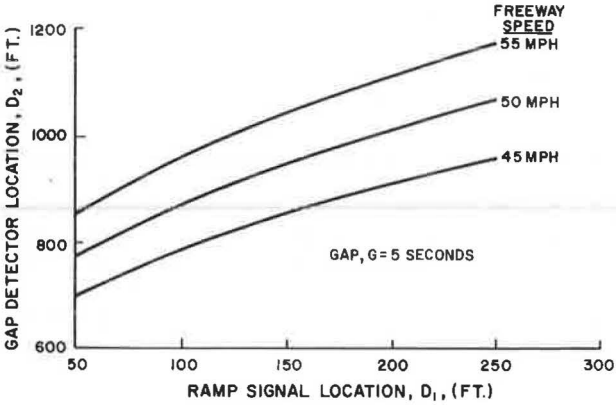

Figure 4. Gap detector and ramp signal locations for metering passenger vehicles.

The location of the gap/speed detector, D_A, should be determined in conjunction with the location of the ramp signal. The distance between the gap detector and the ramp nose should not be less than the distance covered by a freeway vehicle, at the highest speed expected during control, during the time required for a ramp vehicle to travel down the ramp plus the time required to measure a gap. In other words, the closest permissible location of the gap detector is such that the freeway travel time equals the average ramp travel time plus the maximum service gap. This relationship is shown in Figure 3. The ramp travel time depends on vehicle operating characteristics and is a function of the ramp signal location (3). When the truck control function is used, the ramp travel time should be that of the average truck and also the gap, G, should be the acceptable gap for trucks. The use of multi-vehicle metering will also increase the maximum service gap, requiring that the gap detector be located further upstream.

Figure 4 shows the trade-off between ramp signal location, gap detector location, and freeway speed based on the ramp travel time characteristics determined on the Gulf Freeway (3). In many cases the location of the gap detector will be limited by an upstream off-ramp, thus determining the location of the ramp signal. In other cases, the location of the ramp signal may be limited by a short on-ramp, thus determining the position of the gap detector. Certain geometric configurations may even preclude gap acceptance control, except at low freeway speeds. At locations where no limitations exist, the position of the ramp signal should be established first and the gap detector then positioned accordingly. In general, the ramp signal should be so located that the check-in detector will not be actuated by vehicles that travel along the frontage road without entering the ramp. The signal should be as close to the nose as possible in order to reduce the variability in ramp travel times, but should be far enough away that ramp vehicles can attain fairly high speeds. A ramp signal located 150 to 200 ft from the nose yields quite satisfactory operation.

As discussed, the gap detector location is based on the highest freeway speed at which control is to be exercised. When the speed drops below this value, the travel time between the gap detector and the ramp nose increases, thus introducing an additional time factor. This additional time, termed the "delay" or "projection time", discussed later in this paper, is the time between the instant at which the gap is determined to be larger than the service gap and the instant at which the ramp signal indication should be turned to green.

On the Gulf Freeway, the gap sensors are 6 ft by 6 ft loops. Where double loops are used to sense speed, the leading edges of the loops are spaced at 18-ft intervals. These sizes operate fairly satisfactorily, but problems can be created when a lane-change takes place over the loop pair. Furthermore, where a 6 ft by 6 ft loop doubles as a counting detector, it will undercount when stop-and-go conditions occur because a vehicle may enter the detection area before the previous vehicle has left. Point sensors would therefore be preferable.

Because the gap detectors are located some distance upstream from the ramp nose, gaps and speeds in the merging area may differ considerably from their measured values (3). In order to minimize the effect of this instability, control systems involving four pairs of detectors upstream from the merging area are now being installed at three ramps on the Gulf Freeway. These systems will switch to a different loop pair

when the freeway speed changes by a certain amount, thus always using a loop pair as close to the merging area as possible. The success of these controllers has not yet been evaluated.

GAP PROJECTION

In attempting to fit a ramp vehicle into a gap on the freeway, the controller must, after determining that a gap is at least of a certain size, "project" this gap downstream for a certain time period (determined by the speed of the gap) before turning the signal to green. In other words, upon observing an acceptable gap, the controller turns the signal green after a certain "projection time" or "delay". This delay depends, of course, on the ramp travel time, the location of the gap detector, the speed of the gap, and the size of the critical gap. Its magnitude, D, should theoretically be such that the travel time, T_f, of the lead vehicle of the gap, between the gap detector and the nose, equals the ramp vehicle's travel time, T_r, from the instant that the signal turns green until it reaches the nose, plus the size of the service gap, T, plus this delay—i.e.,

$$T_f = T_r + T_s + D \tag{1}$$

Since the ramp travel time is a constant and the service gap can be included in the projection time ($D = D + T_s$), the projection time is a function of the freeway travel time and, therefore, a function of the freeway speed and of the gap detector location:

$$D = f(T_f) = f'(u_f, D_a) \tag{2}$$

For any fixed gap detector location, the projection time is, therefore, a continuous function of the freeway speed. However, since the gap detector location will change from one ramp to another, it is necessary that the controller be designed so that the gap projection vs freeway speed function can be adjusted to fit a certain detector layout, rather than be specifically designed to fit a certain detector layout, or, alternately, the detectors be placed so as to conform to the controller.

In the first-generation analog controllers now in use, this projection time, or delay, is handled by means of four level monitors. These same level monitors are used to define the service gap vs freeway speed function described earlier. Each speed range, defined by two level monitors, has associated with it a delay setting that can be adjusted with a dial. As a result, Eq. 1 is not always truly achieved, but is, in fact, approximated by a four-step function.

In attempting to fit the time-space trajectory of a ramp vehicle into that of a freeway gap, several errors can arise over which the system has a certain degree of control: (a) errors in the predicted freeway travel time caused by speed instability, (b) errors caused by the variability in ramp travel times, and (c) errors caused by approximating the delay function by a step function. Errors of the third type can be completely eliminated by using a digital computer or an analog controller that can solve the projection time vs speed function. It can also be reduced by using more level monitors. Errors caused by speed instability can also be considerably reduced by projecting vehicles rather than gaps (3). This, however, increases the complexity of the controller. In other words, the error can be reduced at increased cost. The designer should weigh the effectiveness of reducing these errors against the cost of reducing them. The best accuracy that can be attained is defined by the distribution of ramp travel times.

Studies performed on the Gulf Freeway have indicated that when a level monitor system is used the speed groups may, for all practical purposes, be equally spaced, with the projection time set for a speed at the midpoint of each speed group. Disregarding errors introduced by speed instability, a four-level monitor system, is, at best, about 80 percent as effective as a system using the theoretically correct projection time. The second-generation controllers now being installed on the Gulf Freeway do not make use of level monitors, but project gaps based on the actual speed of the lead vehicle of the gap.

DISPLAY REQUIREMENTS

The displays used in conjunction with merging control systems consist of two types: displays serving to indicate the operation of the controller itself and displays serving as driver communication devices. Displays of the first type are usually mounted on the face of the controller and are required to visually monitor the operation of the control system. In a strictly operational (as opposed to research) instrument, such displays can be minimized. However, it is advisable to have at least a small pilot light indicating the operation of each controller feature and the actuation of each loop. This greatly enhances troubleshooting and facilitates maintenance and checking out of the instrument. The driver communication devices used to date consist essentially of two types: ramp signals and advance warning signs.

Ramp Signals

The ramp signals used on all three freeway surveillance and control projects (Houston, Chicago, and Detroit) are essentially standard traffic signals. The signals used in Houston and Detroit are mounted on the left-hand side of the ramp and bear the legend "STOP HERE ON RED" (Fig. 5). This legend is quite important. On the Detroit project, the legend "STOP HERE ON SIGNAL" was used at first, but later changed because it apparently caused considerable confusion. On the Chicago project, two signals are used on each ramp, one placed on either side. These signals have only the red and green indications and bear the legend "WAIT HERE FOR GREEN". Operation without the amber phase is actually preferred, but some states require that the signals must conform to the code on uniformity of standard traffic control devices because they have all the appearances of conventional traffic signals. It is felt that a new type of ramp signal should be designed and tested—one that is completely different from any standard traffic control device and is simple yet effective. The ramp signal is in some respects the most important single component of the control system because it is the device that actually exerts the control over traffic operation. Surprisingly little research effort has been devoted to its design and effectiveness.

In Chicago and Detroit, stop-lines are used in conjunction with each signal. However, studies performed at several ramps on the Gulf Freeway revealed that stop-lines have

Figure 5. Ramp control signal used on the Gulf Freeway.

Figure 6. Advance warning sign used on the Gulf Freeway.

no effect on the stopping behavior of ramp vehicles. Consequently, stop-lines are not used on the Houston project.

The location of the signal with respect to the ramp nose has been discussed earlier. The signal head should be mounted so that it is approximately at a driver's eye height, and it should be turned so as not to be readily visible from the freeway.

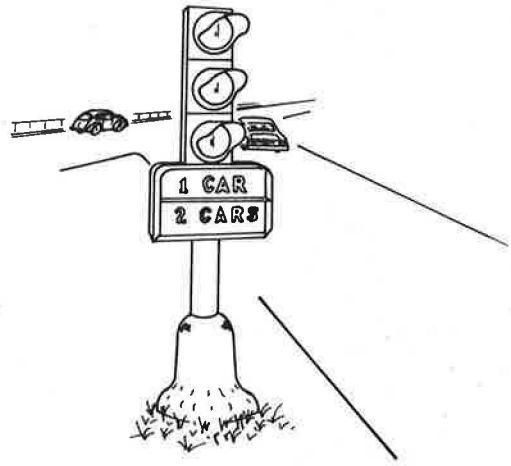

Figure 7. Experimental ramp control signal for multi-vehicle metering.

Advance Warning Sign

On all three projects mentioned, some type of advance warning sign is placed upstream from the ramp signal. The type used in Houston is shown in Figure 6; it consists of a black legend on a yellow diamond-shaped background, with two alternately flashing amber signals. The signs used in Chicago and Detroit are essentially similar, except that the legend on the Chicago signs reads "RAMP SIGNAL AHEAD." In the absence of any evaluation of the effectiveness of advance warning signs, it is felt that they are generally desirable.

Multi-Vehicle Metering

As mentioned earlier, the metering of multi-vehicle platoons has not been tested seriously to date. An experiment planned on the Gulf Freeway will involve the use of a ramp signal (Fig. 7). This signal still includes the conventional traffic signal, but will have an additional signal to indicate that one or two vehicles should proceed past the signal.

Figure 8 shows a suggested ramp control signal for multi-vehicle metering. It has a red "STOP" display and three green displays indicating that one, two, or three vehicles should proceed past the signal. When the controller is ready to meter a three-vehicle platoon, the signal will indicate "3 CARS" and, then, on a fixed-time basis, turn to "2 CARS", "1 CAR", and back to "STOP". This display is suggested as a simple, potentially effective, nonstandard signal.

Another proposed method of multi-vehicle metering involves the metering of vehicles alternately from two parallel queues. Such a method will usually require reconstruction of an existing ramp.

Figure 8. Suggested ramp control signal for multi-vehicle metering.

CONTROLLERS

The merging controllers developed and tested on the Gulf Freeway were all of the analog variety. The first prototype controller (Fig. 9) installed on the Telephone Road inbound entrance ramp of the Gulf Freeway in March 1966 was quite an elaborate instrument. It included three sets of level monitors with ten levels in each set, a gap computer, a gap projector, and a signal controller, together with various displays of speeds, volume, gap projection, and so forth. From this prototype controller, the first-generation controllers were developed (Fig. 10) and installed on the Gulf Freeway in October 1967. These controllers operate essentially as the pro-

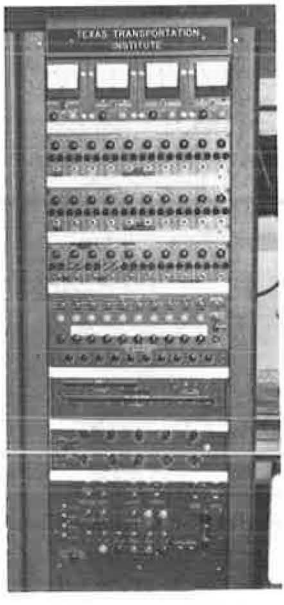

Figure 9. Prototype merging controller.

totype controller, but many features found unnecessary on the prototype have been eliminated. These controllers utilize four level monitors to select the service gap and projection time at various speed ranges, as discussed earlier. Furthermore, they consist of gap computer/projectors and signal controllers.

The construction of three new second-generation controllers was initiated in November 1967, but they had not been completed by the time this report was written. These new controllers will project gaps based on the actual speed of the lead vehicle of the gap, rather than on the speed range of the average freeway speed, as is the case with the first-generation controllers. Speeds and gaps will be measured on the freeway with four sets of closely-spaced detectors. The controller will automatically select one set to direct the operation at any one time, based on the freeway speed prevailing at the time. It will also include the multi-vehicle, slow-vehicle, and truck metering features discussed earlier. These controllers will be quite versatile in that all control variables will be adjustable and all optional features will be switch-controlled so that they can be turned off. As a result, this research instrument can be thought of as several controllers built into one chassis. It will be used to study the effectiveness of controllers of varying degrees of sophistication.

In July 1967, an IBM 1800 digital computer was installed in the control center (Fig. 11) in order to develop, implement, and evaluate system control measures on the freeway that would operate the freeway as a system rather than as eight independent entrance ramps. Computer control on a limited basis was initiated in March 1968. The versatility of this instrument has led to the hypothesis that even isolated entrance ramps can be better controlled with digital equipment. Since both the process inputs and the process outputs are digital signals (contact closures), the control of the merging process is by nature a digital problem. There are many small digital computers on the market (small in the sense of limited computing power and physical size) that are ideally suited to the job. These small computers are, however, generally too powerful and expensive for the control of a single entrance ramp, but are believed to be an economically feasible way of controlling three to six entrance ramps, or groups of ramps in the same interchange. It is believed that a small programmable binary digital computer can be developed that would not only be economically competitive with analog equipment, but also would be more versatile

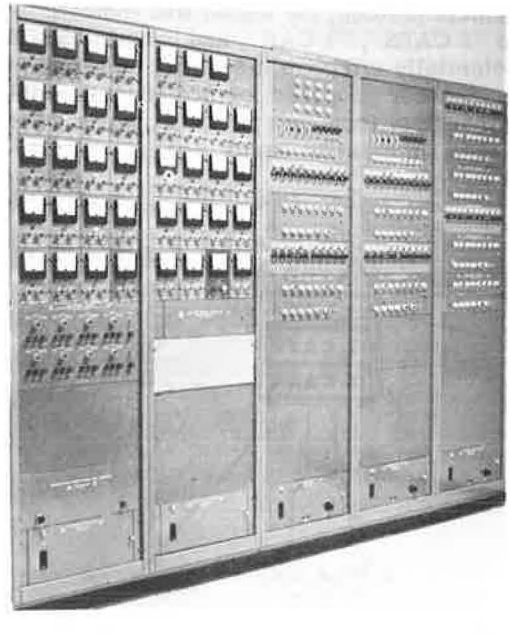

Figure 10. First-generation merging controllers.

Figure 11. Digital computer data acquisition and control system in the Gulf Freeway Surveillance and Control Office.

and more effective. Research into the development of such a controller is strongly recommended.

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