I = moment of inertia of normal cross-sectional area of column with respect to gravity axis of bending.
L = total length of column.
M = bending moment; M_0 greater end moment; M_1 = smaller end moment; M_x = bending moment x distance from origin; M_m = maximum bending moment.
P = compressive axial load on a column; $P_e = \pi^2 EI/L^2$ is the Euler load for straight column with pinned ends. P_c = critical load for any column; P_y = load that first produces yielding; P_n = applied load multiplied by an approximate safety factor n such that the maximum fiber stress does not exceed f_y, the yield point strength of the material.

$$Q = \frac{\pi^2}{\pi^2 - p^2L^2} = \frac{1}{1 - (P/P_e)} = \frac{1}{1 - (s/s_e)} = \frac{P_e}{P_e - P} = \frac{s_e}{s_e - s}$$

S = section modulus, I/C.
α = $(L/2r)\sqrt{P/AE} = pL/2$ for general use where safety factor n is not involved or where safety factor $n = 1$; also $\alpha = (L/2r)\sqrt{Pn/AE}$ where P is the working load and n is the factor of safety; 2α is simply twice the above defined α values.
Δ = maximum initial deflection at mid-length of an initially curved column; at mid-length the initial ordinate $y_0 = \Delta$; $\Delta c/r^2$ = crookedness ratio.
π = 3.1416.

Design of Toll Plazas from the Operator's Viewpoint

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The distinguishing feature of the toll facility is the tollgate. While the function of the gate is the seemingly simple one of collecting and processing tolls, the present-day version, handling high volume traffic presents operating requirements of considerable complexity. Not only must the integrity of the collection system be assured, but inasmuch as the tollgate is an obstruction in the roadway, its restriction on the free movement of traffic must not be inconsistent with the capacity and standards of the facility it serves.

This paper presents some observations of the authors pertinent to the design of toll plazas drawn from their experience on toll bridges operated by the California Division of Highways.

● THE single feature that distinguishes the toll highway facility from the so-called free highway facility of like character and standard of design is found in the construction provided for the collection of tolls—the tollgate. Every other construction and standard which progressive engineering has developed for our modern highways can be found as well in one type of facility as the other.

It would be difficult to find a phase or detail of design or construction common to these facilities which has not been dissected, analyzed, and discussed voluminously, if not finally, in our technical proceedings, journals, and books. The engineer researching any particular problem is generally confronted with the necessity of limiting his choice of literature rather than with a scarcity of information.

A similar plethora of material confronts inquiry into the general subject of toll facilities. Augmenting the many excellent reports and articles covering the various major projects constructed pre-1940, there has appeared a voluminous and growing literature on toll road developments in this country since the end of World War II. But insofar as this literature differs from the technical literature of general application in the highway field, it deals almost exclusively with the economic, legal, and policy aspects of the subject. There is a surprising meagerness of material on that unique feature of the toll facility—the tollgate. This is particularly so with respect to information bearing on the performance of toll plazas as built and operated.

The authors draw upon their experience of the past 18 years on the management staff of the San Francisco-Oakland Bay Bridge and other bridges operated by the California Division of Highways to present some observations applicable to the design of toll plazas. The principal source of information has been the Bay Bridge—a multi-lane structure carrying maximum traffic volumes. Conclusions presented are therefore particular to this bridge, but are believed to have value for any toll plaza application.

PERTINENT DATA ON THE SAN FRANCISCO-OAKLAND BAY BRIDGE

The principal design features of the San Francisco-Oakland Bay Bridge have been adequately described in the technical literature and we mention here only those data which have value for this paper.

The bridge is a two-level structure crossing San Francisco Bay in a general east and west direction. The upper deck, 58 feet wide between curb faces, provides for six lanes of automobile traffic. The lower deck provides three lanes for truck and bus traffic on a 31-foot roadway flanked by two inter-urban railway tracks on the south side.

The westerly ramps of the bridge are located close to the business, financial, and industrial center of the City of San Francisco, and the easterly end is on the waterfront of the City of Oakland, the principal city of ten which comprise what is locally known as the East Bay. Arterial highways and freeways and city streets distribute traffic on both ends to the urban areas and the state Highway System.

The urban area served by the bridge has a present population of about one and a half million people—800,000 on the San Francisco side, and 750,000 in the East Bay cities. These cities furnish 85 to 90 percent of the bridge traffic. It is estimated that the equivalent of 12 percent of the urban population crosses the bridge daily—40,000 in inter-urban trains and buses, and 150,000 in automobiles, long haul buses, and commercial vehicles. It is apparent that with the daily movement described and the equality of population at both termini, the bridge is, in effect, the main street of the metropolitan Bay Area.

TRAFFIC DATA

Eccept for the war years of 1943 through mid-1945, the bridge traffic has increased steadily, if somewhat erratically, year by year. In 1937—the first full year of operation—the average daily traffic was 25,000 vehicles, and the annual total, 9,100,000. In 1953, the daily average was 87,500, and the annual total, 32,000,000. The daily variation in traffic from the average does not exceed about 10 percent. Buses average 1.5 percent of total traffic, and trucks, 8.5 percent. The daily flow of traffic over the bridge is about evenly divided between the east and west directions. Peak-hour volume in the major direction is only slightly less than 6 percent of the average daily traffic for both the morning and evening peaks (west in the morning, east in the evening). In the minor direction, it is 2¾ to 3 percent in the morning, and 3½ to 4 percent in the evening. The peak traffic occurs for about 1½ hours both morning and evening, Mondays through Fridays.

Data on annual traffic composition are given in Table 1, and typical peak-hour traffic in Table 2.

ORIGINAL BAY BRIDGE TOLL PLAZA

The toll plaza is located on the East Bay shore on made ground about 3,800 feet from the easterly end of the structure proper.

As originally constructed, the cross section of the west approach highway between the bridgehead and the toll plaza consisted of six 10-foot auto lanes, leading from the upper deck, flanked on each side by two 11-foot truck and bus lanes. Five-foot curbed division strips separated the auto lanes from the heavier traffic. The division strips terminated about 500 feet from the center line of the tollgates thus providing an unobstructed conform (convergence-divergence area) from traffic lanes to toll lanes. On the opposite side of the gates, the conform area was similar but the road cross section changed to provide three lanes for mixed traffic in each direction, separated by a 5-foot curbed median strip.

The tollgate layout consisted of 16 lanes of the familiar "onside-offside" design. (The quoted terms refer to the side on which the driver pays toll with respect to his position in the vehicle.) The two lanes on the extreme right in each direction were equipped with platform scales for the weighing of trucks—one 60-foot and one 30-foot scale in each direction. In the initial operation, these scale lanes were also used for the passage of buses (weighing omitted). The remaining 12 lanes were designed and equipped as auto lanes. The out-to-out width of the tollgates was 195 ft. 6 in. as compared with the 114-foot out-to-out width of the traffic lanes on the west approach.

On one end (south) the tollgates are flanked by the westbound main track of the bridge-owned inter-urban electric railway, together with set-out tracks and maintenance yard. On the other (north) end is located the building which serves operation and maintenance activities. Original design contemplated that future expansion of the tollgates would be to the north; that is, on the opposite side of the operations building from the initial gate layout.

TABLE 1
SAN FRANCISCO-OAKLAND BAY BRIDGE
ANNUAL TRAFFIC BY CLASS

	Cars	Unclassified (passes)	Buses	Trucks	Total
1952	26,772,974	1,332,280	428,464	2,553,925	31,087,643
1953	27,532,367	1,334,466	405,633	2,575,001	31,847,467

TABLE 2
SAN FRANCISCO-OAKLAND BAY BRIDGE
TYPICAL PEAK-HOUR TRAFFIC

	Cars	Buses	Trucks	Total
Friday, Jan. 15, 1954				
7:00–8:00 a.m. E.	2,295	57	233	2,585
W.	4,611	123	376	5,110
4:30–5:30 p.m. E.	4,172	102	414	4,688
W.	3,167	49	284	3,500
24-hour total				90,120
Monday, July 12, 1954				
7:00–8:00 a.m. E.	2,139	49	219	2,407
W.	4,587	104	415	5,106
4:30–5:30 p.m. E.	4,529	97	439	5,065
W.	2,912	44	288	3,244
24-hour total				89,889

TOLL PLAZA CHANGES

As traffic increased on the bridge, so did difficulties in processing vehicles through the toll lanes. The critical volume appeared to be in the vicinity of 60,000 vehicles daily on the prevailing pattern. This figure was reached in mid-1942 but dropped to 50,000 daily with the imposing of gasoline rationing on December 4, 1942. By stages a number of projects were undertaken to improve efficiency in handling of traffic.

The initial project during war years provided additional traffic lanes for trucks and buses. Because a substantial percentage of the heavy truck traffic consisted of military vehicles not subject to toll under existing agreements, the construction of an additional traffic lane in each direction permitted such vehicles (and buses) to be routed through a passenger car toll lane. By thus bypassing the overtaxed truck lanes, the military and bus traffic was expedited and truck traffic correspondingly relieved of delays.

With the lifting of gasoline rationing on August 15, 1945, traffic across the bridge jumped almost overnight from 55,000 vehicles per day to 70,000 per day. Due to material shortages, we had to suffer for a time but eventually constructed a 4-lane truck and bus plaza to the north of the operations building. It was completed in 1949. With westbound commercial traffic diverted to this plaza, two additional lanes were available for automobile use in the main (south) plaza. But, more important, the construction of the new plaza permitted improvement of the approaches to the south plaza to provide a conform about 1,400 feet long in place of the previous 500-foot length. The construction materially improved the utilization of the toll lanes by patrons.

Coincident with the completion of the north plaza, installation was commenced on more modern toll registration and recording equipment. Passenger lane equipment was less complicated than freight lane equipment and was completed first. It has given about five years of satisfactory service. Truck lane equipment has been in service about two years but we have not yet obtained consistently reliable performance.

A project is now pending to reconstruct and extend the existing plazas to serve the ultimate capacity of the bridge. It is planned to provide 15 "onside" lanes in an extended north plaza consisting of 11 passenger lanes, one bus lane, and three truck lanes. The south plaza will then be reconstructed to provide a bank of like number.

These various changes in the toll plaza layout and equipment, combined with our more or less continuous studies and observations of plaza operation under maximum traffic loads, have led us to a number of conclusions which, had they been known to the designers at the time of original construction, would have resulted in a much better plaza. To the extent permissible, they have been applied on our design for the proposed new plaza.

TOLL SCHEDULES AND THEIR EFFECTS

A complex toll schedule can affect both the design and operation of a toll plaza. Adverse effects arise principally from an unnecessarily large number of classifications, the special privileges granted to certain classifications and the method of application of tolls. Economy in construction cost and efficiency in operation and traffic handling are promoted by the simplest possible toll schedule, and one geared to the volume and composition of traffic in the peak hours. Every effort should be made to have not more than 10 classifications.

A large number of classifications may require development of special toll collection equipment with its attendant costs and potential delays. Margin for error and toll manipulation in collection will be increased and a corresponding burden placed on supervisors to maintain the integrity of the system. Special privilege may be in the form of commutation books for automobile patrons, and credit accounts for trucks. Either can, under certain circumstances, increase the burden of handling traffic through the lanes.

Method of application will principally apply on trucks; that is, whether toll is specified on the basis of:

(1) Type of vehicle (flat rate or mileage)
(2) Axle count
(3) Axle count plus tire count
(4) Gross weight determined by scale weight
(5) Manufacture's rated capacity
(6) Length of journey over facility (toll roads), or some combination of these methods, or others

Commutation books, if sold in the toll lanes, add another classification to register equipment for each form sold and, for each sale made, effectively double the time to pass a vehicle through the lane. When sold on a calendar-month basis, sales are concentrated in a few days at the beginning and end of the month and, as most commuters are peak-hour riders, these sales can produce congestion and delay at traffic volumes much below the capacity of the plaza. If the books are sold on a 30-days-from-date-of-purchase basis, the sale of books is spread throughout the month but passage time is increased through the lanes in checking the book for validation date. Books may be sold on an off-plaza basis but this poses some problems in the control and supply of books and generally does not serve the patron as conveniently as bridge sales unless a large number of sales outlets are provided. Other forms of selling commutation rates prevail with toll facilities but, as far as we are aware, all have the disadvantage of slowing traffic at some stage of the transaction.

The Bay Bridge, until about two years ago, sold two sizes of commutation book—a 40-trip and 50-trip book. Each was sold on a calendar-month basis. About 9 to 10 percent of the car patrons purchased one form or other of the books. This amounted to 4,000 to 5,000 sales per month concentrated in the peak hours on about three days. The books had certain added features which, when used, would increase the time of passage through a lane from 2½ to 3 times the normal. It was not deemed policy to abolish the books. To ease an intolerable traffic situation, the problem was partially solved by selling only one form of book, good for the remainder of the month in which sold and all of the succeeding month. The added features of the previous books were eliminated as no longer necessary. This procedure gave substantially the same privilege as formerly, effectively spread sales throughout the month, and did not increase the use. Color coding identified the validity of the book so that no time was normally lost for examination by the collector. It is to be noted that this solution did not lessen the total delay (except in the elimination of the added features referred to); it merely spread the delay over 25 days or so rather than three, and thus made it tolerable.

The method of applying toll to trucks is probably the toll decision most affecting either the design or operation of a toll plaza. If tolls are on a cash basis only, a truck toll transaction will average two to three times as long as a passenger car transaction. If credit is granted, the upper limit may quadruple the car toll time.

When it is anticipated, or known, that maximum traffic volume must be handled through a barrier plaza, probably one of the first four methods of toll application previously mentioned will be used—flat rate, axle count, gross weight, or axle count plus tire count, although a number of the eastern bridges and tunnels use type of vehicle and manufacturer's rated capacity. Each has merit for particular conditions and also disadvantages.

Flat rate tolls will have application in barrier plazas where unit tolls are assessed, the average toll is low, and the maximum number of trucks must be handled through the minimum number of lanes. On a flat rate cash toll, trucks can probably be handled through a lane at a rate of 300 per hour. The flat rate has no equity basis and hence will not generally be popular with patrons except in the limiting circumstances cited.

In our analysis there is little advantage in any of the next three methods from the standpoint of speed in the handling of traffic. What little there is probably favors them in the order named. It is to be noted that the first and third are really extensions of the flat rate which attempt to establish an equity basis by relating the toll to the gross weight capacity in a roundabout way. The advantage of the straight axle-count method lies in the ease of checking toll registrations against axle count record if there is a uniform charge per axle. This advantage does not extend to the third method inasmuch as there is no way to record the extra tire on dual wheels. This method also makes the number of truck classifications unncessarily large.

The merit of the gross-weight method is that it places toll on the same basis as the trucker charges for hauling and is clearly equitable. It has the disadvantage that toll registration and supervisory equipment is more complicated for automatic operation than the axle-count method; the cost of platform scales and scale pit construction is an added expense both as to first cost and maintenance.

By any of the last three methods named, the possible capacity of a truck lane is 225 to 250 trucks per hour on a cash basis. Writing up charge tags to credit customers will reduce these figures substantially—about 20 to 25 percent in Bay Bridge experience.

It should be noted that considerable work has been done by at least one manufacturer of toll recording equipment on the use of dynamic scale equipment for weighing trucks. Claim is made that trucks can be processed through a toll lane at a rate of 300 per hour on either a cash or credit basis.

TOLL COLLECTION EQUIPMENT

It is trite, of course, to say that the only reason for the tollgate is to collect and account for the money, or its equivalent, assessed each vehicle using the facility. These moneys will have been indentured to the service of the bonds which made the construction possible. By agreement, they may also have been allocated in part to cover insurance, operation, and maintenance costs. There is therefore an obligation on the owner to assess and process the tolls strictly in accordance with prior covenants to the bond-holders and the public, and to guard, insofar as it is possible, against diversion of collections. Obviously any looseness in processing of the tolls can lead to substantial losses.

Consideration must also be given to the welfare of the toll collector. In most organizations he will be a carefully screened and valuable employee. Good collectors are rather difficult to come by and it would be an unfortunate circumstance if looseness of system or inferior equipment encouraged them to dishonesty. The collector is also entitled to equipment which can operate at high speed and without unreasonable physical demand on him.

Toll collection equipment is very specialized. Rigid requirements must be met as to accuracy, ruggedness, speed of operation, ease of maintenance, and tamper-proof design. Not only must these requirements be met but they must have been demonstrated over an extended period of time. A traffic-busy toll plaza is not a proper place to iron out the deficiencies of inadequate equipment.

Fortunately for the engineer, basic equipment of adequate design is available but equally unfortunate is the circumstance that the market for this equipment is comparatively small. Thus, competition is limited and prices relatively high. Because the equipment is not suited to mass production methods, delivery dates have considerable uncertainty. This uncertainty is compounded if special features of the toll schedule cannot be accommodated on the basic equipment and require development work.

In the equipping of a toll plaza, the role of the engineer is not likely to be that of a designer, but rather that of an analyst of available equipment and as a specification writer around his specific needs. In the modern high-traffic-volume toll plaza, the requirements for compactness, remote recording, and the features mentioned above will almost certainly call for electro-mechanical rather than mechanical equipment. It is well to bear in mind that a busy lane in a plaza may handle as many as 2½ million cars in a year. This is a substantial number of operations for a working part to carry and still maintain accuracy. It is also well to note that the working parts in the axle counter circuit in this same lane will have twice as many operations in the same period. Obviously not only ruggedness, but also ready access and ease of maintenance are prime requisites. All components should be of unit design and either set-screw mounted or have plug-in connections for easy removal.

It is not the purpose of this paper to describe in detail the various types of collection equipment that may be used. An interchange plaza on a toll road will have the same functional equipment as a barrier plaza charging a unit toll, with the added feature that the register equipment at an entrance plaza will issue some form of tabulating or punched-card ticket which is carried by the patron to his exit plaza where the card is surrendered together with the toll and processed through the exit register.

On the Bay Bridge, the following basic equipment is installed for a toll lane:

1. A treadle-actuated counter which counts each axle passing through the toll lane. Axles crossing the treadle in opposite directions are segregated and accumulated separately.

2. A remote electric register, installed in a locked room in the administration building, which prints a record of the total axle counts in each direction, the total transaction count of each classification passing through the lane, the total cash freight transactions (in freight lanes), the credit transactions (in freight lanes), the key number of the collector on duty, and the time of each printed impression on the tape.

3. A key button box mounted adjacent to the door of the tollbooth in the location determined to be the most accessible to the collector. The collector opening a lane inserts and turns his key in the key receptacle. This unlocks his button box and causes a print to be taken of the register counters. Thereafter, on completing a transaction, he depresses a button of the proper classification. This adds one count to the corresponding counter unit in the register. It also displays the proper symbol on the overhead classification indicator (mounted on the canopy fascia) and sounds a bell to notify the patron that the toll has been recorded.

4. A classification indicator mounted on the canopy fascia and indicating in illuminated numerals visible for at least 500 feet, the transaction last recorded by the collector on his button box. A dark period separates each transaction.

5. Each freight lane, in addition to the foregoing devices, is equipped with automatic toll-computing and printing equipment. A scale dial attachment converts the indicated weight into the amount of the toll. For a charge transaction, the collector inserts a stencil plate presented by a credit customer into a slot in a printing device. The stencil plate bears the name of the customer, the account number, and year. The collector then depresses the classification button corresponding to the number of axles on the vehicle. This causes a ticket to be printed and issued in duplicate. The ticket records the transaction number, the amount of toll, the information on the credit identification plate, lane number, date, and time. The amount of the transaction is simultaneously added to the credit totalizing counter of the register.

When a cash truck transaction occurs, no credit plate is inserted in the printer. When the collector depresses the button corresponding to the axle classification of the vehicle, a ticket is printed and issued, but the space reserved for the credit plate information is blank. The amount of toll is automatically totalized on a cash transaction counter of the register so that the end of the collector's shift the total sum of all cash registered by him is available to the auditor.

The ticket for each transaction is issued in duplicate, the original going to the vehicle driver. The duplicate goes to the billing department and, after microfilming, is returned to the customer with his monthly statement. Each ticket is printed with a consecutive serial number and automatically advanced on each transaction. In this way each collector is held responsible for every ticket and it is impossible to divert a ticket without the knowledge of the accounting department.

6. A detail transaction tape machine which is installed at a convenient location for direct observation of the toll lanes, and can be remotely connected into any toll lane register. This detail transaction machine automatically prints the classification number, axle count, and time of each transaction in the selected lane during the period of check. This record is compared with visual checks made by independent observers during the same period. Errors, honest or dishonest, are detected beyond doubt and the collector held to account.

7. Traffic accumulating machine. This machine records and prints hourly, or a shorter period if desired, the up-to-the-minute cumulative traffic by lanes and by direction. It performs no collection function but provides a record of traffic performance for the traffic engineer or others interested.

The above described equipment was purchased in 1949 at a cost of $270,000 for 20 lanes (6 freight lanes, 14 passenger lanes). Installation cost was about $30,000, or a total cost of $300,000. On the basis of 30 million vehicles crossing the bridge annually at the present time, this represents a cost of one cent per vehicle if written off in one year. On a capital recovery basis at 4 percent for 20 years life, and a reasonable allowance for maintenance, it amounts to less than 0.1 cent per vehicle.

To complete the story on collection equipment, it should be recorded that the passenger lane equipment has given excellent service. The freight lane equipment has not been so satisfactory. Two years after completion of installation it has not yet been brought up to a satisfactory performance standard. We are still working on it.

Also of interest are some figures on accuracy in recording and collections. Collectors are not required to make good their shortages (except for proved dishonesty), and are not permitted to keep overages. A good collector is expected to collect with an error not greater than $0.25 per $1,000. In 1952, with collections of $9,305,000, the collectors were over registration by $1,490, and short $1,386—a net overage of $104. In 1953, with toll collections $9,546,000, the overage was $1,341, and the shortage $1,126—a net overage of $215.

On the axle counter record, collectors exceed counters about 1:1100, and counters exceed collectors about 1:12000. The failure of counters in the first case can be fairly well explained by skipping of motorcycles and auto trailer axles. The second ratio represents collector error or failure to perform.

TOLL LANE PERFORMANCE

The desirable plaza would be one that had a traffic volume capacity just slightly greater than the peak hourly volume presenting itself to the plaza. Even here, if the excess margin is too narrow, half-hour peaks can establish a congestion condition that may be difficult to overcome for the entire peak period. Traffic once congested—stopping, starting, surging—is difficult to get moving again in uniform flow. Regardless of this circumstance, it will generally be the peak hour traffic and its composition that will control.

It is of some interest to contemplate annual traffic figures on some facilities that are known to be operating at peak-hour capacity, together with their toll lane facilities. A selected few are shown in Table 3.

Since all of these facilities are operating around peak capacity and undoubtedly have considerable back-up during peak hours, it would appear that somewhat more than one toll lane should be provided for every 1.5 million vehicles on the annual basis. It is to be noted here that the composition of traffic, which varies considerably with the above facilities, does not seem to be so critical as on an hourly basis. The figure appears to be useful for a rough estimate on barrier plazas handling mixed traffic.

TABLE 3

Facility	Year	Annual Volume, Millions	No. of Toll Lanes	Average Annual Traffic/Lane
Bay Bridge	1953	32	20	1,600,000
Lincoln Tunnel	1952	19.5	12	1,620,000
Holland Tunnel[a]	1954	19.5	12	1,620,000
Philadelphia-Camden Bridge	1953	29.6	20	1,480,000

[a] Dual plaza.

TOLL LANE CAPACITIES

In our studies for reconstruction of the Bay Bridge toll plaza, the fundamental problem was to determine the number of toll lanes that should be provided to serve the maximum traffic volume. This volume could be estimated to a close approximation for the ultimate capacity of the bridge under several differing contingencies that could occur. The percentage composition of traffic in the passenger vehicle, bus, and truck classes was known within reasonably narrow limits, and the pattern of traffic was likewise well established. The determination of the required number of lanes would control the toll plaza and approach road design.

As a first order of business it was therefore necessary to establish the peak-hour performance of a toll lane.

Our experience has convinced us that the maximum number of vehicles can be most efficiently handled through a toll plaza when the traffic is segregated and the individual lanes dimensioned to best serve the group for which designed; that is, passenger car, bus, or truck. If all lanes were designed for mixed traffic, the wider lanes required for trucks and buses would necessarily control, and there would be an appreciable loss of efficiency in passenger car collections which normally constitute about 85 percent of the total volume of traffic. There is no objection, of course, to using toll lanes designed primarily for buses and trucks for passenger cars when traffic in the former is at low ebb.

In our studies of actual toll lane performance on the Bay Bridge, the striking fact was the great variation in vehicles handled per hour through adjacent lanes under similar conditions. Our approach was therefore to determine what we called a basic capacity for a toll lane designed for each group—passenger car, bus, or truck. In the passenger car group, values were determined for both an onside and an offside lane. A similar distinction was not made for the bus and truck groups. With the basic capacity for a lane determined, we then assigned a practical capacity for that lane by multiplying by a factor representing our evaluation of average performance capacities.

In determining basic capacities, the performance statistics of lanes favorably located with reference to the alignment of a traffic lane were selected when the lane was manned by a superior collector and heavy traffic pressure prevailed. For an onside passenger lane, only a few performances exceeded 800 cars per hour, but numerous instances occurred of values between 700 and 800. However, it was our judgment that the lower of these values was about the maximum performance that could be consistently expected from a good collector. This value was therefore taken as the basic capacity of an onside passenger lane under our conditions of operation.

Offside passenger car lanes showed great variation under changing traffic pressures, but under peak conditions handled 88 to 92 percent of an onside lane. The basic capacity of an offside passenger lane was taken as 90 percent of 700, or 630 cars per hour.

Truck lane statistics were similarly studied for performance for cash transactions only as it was felt that the effect of credit charges were properly included in a modifying factor. The basic capacity of a truck lane was established at 223 trucks per hour.

Inasmuch as insufficient bus traffic existed to give a sustained trial period through a lane, the basic capacity of a bus lane was determined from a projection of the time elapsing in individual transactions. It was taken as 400 buses per hour.

It is pertinent to note that, while a value of 90 percent of an onside passenger lane capacity was assigned to the offside passenger lane, this value was only realized under heavy traffic pressure and otherwise favorable conditions. The average performance was only about 65 percent of the onside lane and frequently much lower. When traffic pressure drops and the patron has some freedom of choice, he naturally prefers the onside lane.

Since the values for basic capacity were determined for favorably located lanes under conditions of traffic pressure (congestion) that would not normally be tolerable, and excellence of collector and patron performance and cooperation that could not be insured, it was desirable to apply factors which would result in more realistic average values for design purposes.

Our studies indicated that about 83 percent of basic capacities was the best that could be expected for the average performance in a passenger lane. For truck and bus lanes, 90 percent of basic capacity was justifiable with an additional reduction of 25 percent in truck lanes for credit transactions. Application of these factors to basic lane capacities provided the following figures for practical lane capacities:

1. Onside passenger car lane—580 cars per hour
2. Offside passenger lane—525 cars per hour
3. Bus lane—360 buses per hour
4. Truck lane (cash transactions)—200 trucks per hour
5. Truck lane (credit transactions)—150 trucks per hour

It should be reiterated that these values are for conditions prevailing on the Bay Bridge where the basic auto toll is 25 cents per car and 90 percent of the passenger car transactions are cash. The trucks pay toll on a gross-weight basis and 40 percent of the truck tolls are on a charge basis.

TOLL LANE DIMENSIONS

For efficient handling of traffic, the lateral dimensioning of the various elements of a toll lane is an important factor. When it is recalled that the average passenger toll lane transaction takes place in about six seconds, it is evident that fine adjustments must be made to establish the most favorable condition for consummating the transaction.

The booth must be wide enough to accommodate necessary registration equipment, the cash drawers and other supply shelving, and provide complete freedom of movement for collectors differing greatly in physical proportions. If the booth is too wide, the collector must make unnecessary motions to reach different devices and objects in the booth, and he may also discourage traffic through his lane by hanging back in the booth. The wider booth may also call for increase in the overall width of the plaza and thus further decrease efficiency. If the booth is too narrow, the motions of the collector are hampered with a loss in efficiency and the collector of large physique may be placed in a position of hazard from passing vehicles. In general, one width of booth is satisfactory for a passenger car or bus lane while the truck lane will be somewhat wider. The preferred width for a passenger-lane booth is 3 ft., and for a truck-lane booth 3 ft. 6 in.

The tollbooth island must be wide enough to accommodate the booth and provide curb walks on each side of the booth of sufficient width to afford protection for the collector and booth. If the curb walks are too narrow, protection from overhanging portions of the vehicle or load is not afforded. Moreover, as vehicles frequently overrun the door of the booth, the collector is hampered in collection unless he has sufficient room on the curb to walk to the driver of the vehicle with complete safety to himself. A curb designed with too much width causes the vehicle to stand out too far from the collector and lowers his efficiency by forcing unnecessary motion. A satisfactory top width of curb on the collection side of the booth is 18 inches. A booth designed for onside collection can have a narrower curb in the rear side of the booth as compared with the collecting side. A minimum top width of 10 inches is satisfactory.

It probably should be mentioned here that the tollbooth floor and the curb in front of the booth should be made low in order to make it possible for the collector to perform his work with a minimum of bending over or stooping whenever he has to talk to the driver of a vehicle. This is particularly true with the low overall height of the present-day automobile. At the Bay Bridge, in our latest designs, we are building the tollbooth floors and the adjacent curbs three inches above the roadway through the lane. For protection against traffic, the curbs are stepped-up to a height of 8 or 10 inches beyond the ends of the tollbooth.

The width of the vehicle way through the toll lane is probably more critical than any other element. If the lane is too wide, the driver tends to stand out from the tollbooth, thus forcing the collector to extend a long reach to collect the toll. Both collector fatigue and time lost in the unnecessary motion reduce the capacity of the lane. The wide vehicle lane will also reduce the efficiency of the plaza by adding to the overall width. The minimum width of the vehicle way is established, or course, by the width of vehicles, or vehicles and load, that must be accommodated. However, this minimum width cannot be used even if it could be accurately determined, because of the adverse "claustrophobic" effect of too narrow a lane. This condition would cause drivers to be supercautious in entering the lane, thus slowing down traffic unduly. For the same lane width, the effect will be more pronounced when all the lanes are constructed onside as compared with coupled onside-offside construction.

As a design principle, it may be said that the most efficient lane would be the narrowest possible one consistent with no sense of restriction to the vehicle driver.

Since buses and trucks require wider lanes than passenger cars (whereas the latter are normally about 85 percent of total traffic), it follows that efficiency of the toll lanes, and therefore of the plaza, is promoted by providing a sufficient number of lanes designed for each type of traffic. Mixed lanes cannot be tolerated in a large plaza operating at capacity loads if the distribution of vehicle classifications is near normal.

It is our opinion that the best width of vehicle lane for a passenger car toll lane is 8 ft. 2 in. for onside-offside construction, and 8 ft. 6 in. for all onside toll lanes. For bus lanes, 10 ft. is desirable and 9 ft. 6 in. acceptable. Truck lanes equipped with platform scales will require a 10-ft. 7-in. width, but otherwise may be 10 ft. wide. Truck lanes should either have a coupled onside-offside pair, or an open-ended onside lane, for handling wide loads.

ALL ONSIDE VS. ONSIDE-OFFSIDE CONSTRUCTION

An important consideration in toll plaza design is the problem of whether to use all onside lanes or coupled onside-offside lanes. The latter permit an appreciable reduction in width (about 15 percent) of the plaza.

Prior to 1940 the design of the front seat of a car was such that a driver, as the sole occupant, could readily reach across the seat and pay toll on the offside of the vehicle. However, even with autos of this vintage, there was a studied avoidance, by drivers, of the offside toll lanes for the preferred onside lane. To an appreciable degree he would choose the onside lane even at the sacrifice of time. In the intervening years, the design of automobiles has changed considerably and nearly all manufacturers now provide an ample three-person front seat. It may be said of today's car that it definitely is not convenient for the driver to pay toll on the offside. Even where there are passengers in the front seat with the driver, he frequently objects to having the passenger hand the toll to the collector. In consequence, the tendency to choose the onside lane in preference to the offside has increased. The statistics on toll lane performance on the Bay Bridge indicate that in off-peak hours the offside lanes is only about 65 percent as efficient as the onside lane. In peak hours, with the pressure of extremely heavy traffic, the performance is somewhat better and ranges between 88 and 92 percent of the onside lane. It may be averaged at 90 percent.

This performance factor of 90 percent for the offside lane represents a loss of about 60 cars per hours per lane at practical operating capacity. Since half of the lanes would be offside in an onside-offside plaza, the total loss for the plaza is a fairly substantial figure. For a 12-passenger-lane plaza, it would be equivalent to the loss of 60 percent of one onside lane. It would therefore appear reasonable to assume that the efficient plaza would be one constructed entirely of onside lanes. This assumption would not be entirely correct, however.

The most flexible and economical plaza is the single plaza with swing lanes. Since the volume of traffic flowing in both directions is seldom at maximum in coincident hours, the single plaza permits the assignment of the lanes to favor the predominant direction by reversing the flow in one or more of the center, or swing, lanes. This procedure is not precluded with all onside lane construction, but certain difficulties arise.

For ideal lateral dimensions, the onside lane requires 2 ft. 1 in. more space than the average width of a lane for onside-offside construction. In a 12-lane plaza this additional width requirement becomes the equivalent of two complete lanes. If space is limited, the construction of all onside lanes may not be possible because of the added width if an adequate number of lanes is to be provided, or the advantage of a single plaza may have to be sacrificed by going to a dual plaza. Either contingency will result in some loss of efficiency for handling traffic; the second will greatly increase the cost of construction and, to a lesser degree, the cost of maintenance and operation.

An additional factor inherent in the greater width requirement of the onside lane operates to reduce, or even under some conditions eliminate, the efficiency gap between the onside and offside lane. This factor arises from the fact that it requires about three toll lanes to serve each traffic lane and, since each toll lane, including the tollbooth and island, is somewhat wider than a traffic lane, it follows that about two-thirds of the traffic must fan out laterally from the traffic lanes as the plaza is reached in order to reach an open toll lane. The lateral divergence necessary will be the width of one to four or more toll lanes, depending on the number of traffic lanes served by the plaza. Observation indicates that the traffic efficiency of a toll lane decreases with an increase of lateral divergence. The decrease is rapid when the transition length in which it must be accomplished is short, and is still significant with a long transition. Because of the greater width of the onside lane, the divergence effect is greater than for onside-offside construction. The factor is explored more fully in a discussion of transition areas.

To summarize the argument of all onside versus onside-offside lane construction, we may reiterate that the onside lane as a single unit has a decided advantage over the offside lane, but this advantage decreases and even vanishes as the number of toll lanes required increases. Nevertheless we must recognize the decided preference of the traveling public for the onside lane. Wherever possible this construction should be used.

TRANSITION AREAS

The transition zone between traffic lanes and toll lanes is probably as important, from the traffic viewpoint, as any other element in the plaza. Observation indicates that this importance increases as the capacity of the plaza is approached and that inadequate design of the transition can effectively throttle the attainment of maximum efficiency in the toll lanes. It is also indicated that the exit transition from the toll lanes is, under certain conditions, almost as important as the approach transition. Since the lateral dimensions of the transition are established by the width of the traffic lanes approaching and leaving the plaza and the width of the plaza at the toll lanes, the principal problem is the selection of a proper length for the transition and the development of a geometrical conformation which will invite divergence or convergence in an effective and orderly manner.

On entering the approach transition area in dense traffic, there is a definite disinclination of the driver to diverge from the line of the normal traffic lanes. His action is probably governed largely by his estimate of the hazard

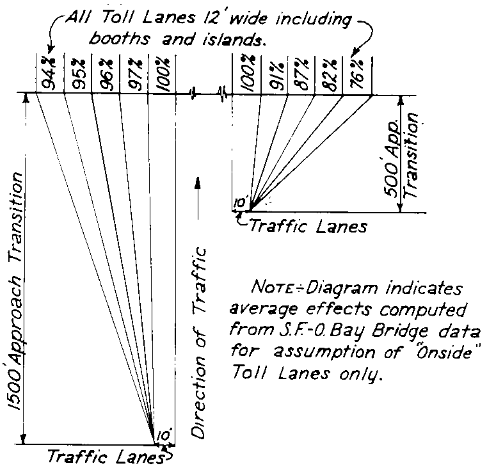

Figure 1. Decrease in efficiency of a toll lane with increasing lateral divergence from a traffic lane.

of a collision with an adjacent vehicle should he change his course. It is also observed that he has a greater objection to divergence to the right than to the left which is no doubt a direct consequence of the relative visibility in either direction.

Bay Bridge experience, with transition lengths of 500 feet and 1,500 feet only, indicates that the driver requires a substantial distance in which to maneuver. A statistical analysis of toll lane performance under these limiting conditions develops the lane factors for approach divergence shown graphically on Figure 1. These data is computed for onside lanes only. The percentage reduction in capacity in diverging lanes shown in Figure 1 was not determinable with any great refinement. In particular the exact conditions of traffic pressure existing for the 500-ft. transition length was not recallable at the time of analyzing the data. However, the information on the figure is substantially representative of effects that may be expected in an approach conform area.

While we did not find it possible to assign a separate numerical value for the divergence effect in exit transitions, nevertheless we can record certain observations which are of value.

When traffic is approaching the plaza it is necessarily slowing up, but on departure from the plaza it is increasing speed. If the driver has no urgent reason for selecting a particular traffic lane on departure, he apparently accomplishes the converging maneuver in the transition area with less hesitation and indecision than he exhibits in the diverging maneuver in the approach to the plaza. He also accomplishes his purpose in a much shorter distance—about half that required on the approach. This is the condition existing in the westbound departure from the present Bay Bridge plaza.

However, a different situation occurs on the eastbound departure from the bridge toll plaza. At points 3/10 of a mile and 9/10 of a mile east of the toll lanes, the highway branches. It frequently happens that a bridge patron, desiring to continue his journey on a particular branch, crosses the bridge and enters the toll plaza from a traffic lane on the side opposite to that which would provide the most convenient access to the particular branch road. To continue his journey after leaving the plaza, he must maneuver across three to five lanes of traffic that is rapidly picking up speed. Apparently many drivers, confronted with this situation on approaching the plaza, will not diverge to the outermost lanes, since it may multiply the number of traffic lanes he must cross after he has passed the toll lanes. Thus the effective use of the toll lanes is affected by difficulties encountered in the exit transition area when patrons have an urgent reason for gaining a position in particular traffic lanes. The solution for this situation is not obvious but it appears to call for a greater exit transition length than would normally be required—possibly as long as the requirement for an approach transition.

LAYOUT OF THE PLAZA

With the volume, composition, and pattern of anticipated traffic known or estimated, the practical capacity of a toll lane in the various classification groups determined, and with the salient considerations on toll lane dimensioning and conform effects in mind, it is an easy step to make tentative layouts of the plaza. As has been mentioned previously, it is desirable from the standpoint of economy in original cost and in operation to have the entire toll plaza designed in a single unit composed of a continuous series of toll lanes and booths. If this is possible, the number of toll lanes assigned to each direction of travel can be varied whenever necessary to accommodate changes in relative traffic volumes. We point out, however, that for the larger toll plazas (say those requiring 10 or more lanes for each direction of traffic), this arrangement loses the advantage or attractiveness which it has in a smaller plaza. The economy in original cost, as well as in operation, is no longer present because of the extremely long transition required and the increased task of shifting traffic markers separating traffic in opposing directions. Furthermore, unless a tunnel or overhead viaduct is provided across the wide plaza, added traffic-accident hazards are introduced whenever vehicles or persons have to cross the main stream of traffic to go to or from the toll plaza operations building or office. When the expected traffic volume is such that a toll plaza of large proportions is indicated, we would recommend a careful study be given to the alternative of constructing a dual plaza; that is, a separate toll plaza for each direction of traffic.

In the layout for the reconstruction of the Bay Bridge toll plaza, this problem was automatically solved by space limitations and the estimate of traffic to be ultimately accommodated. The application of practical lane capacities to the estimated traffic volume determined that slightly less than 25 toll lanes would be required for all onside-lane construction, and slightly more than 25 lanes for onside-offside construction. Since space limitations in the south plaza would not permit construction of more than 15 lanes in the first instance and 16 lanes in the second instance, there was no alternative but to consider a dual plaza. For such a layout, the computation of the number of lanes required was 15 in each plaza, consisting of 11 passenger lanes, one bus lane, and three truck lanes. Thus, the necessity for going to a dual plaza design in this instance required five more lanes than would a single plaza.

There are, of course, many details of design and equipment which must be considered in the development of a toll plaza but which are too varied and detailed to be considered in this paper. Such matters as heating, ventilation, unit and general lighting, architectural treatment, etc., are but a few of the details that must be solved if the toll plaza is to function successfully. Any feature or device which promotes the two things to be accomplished in a toll plaza (the safeguarding of money and expediting of traffic) must receive serious consideration. Our premise is that controlling the activities in a toll plaza involve split-second operation. In view of the short time involved in each transaction, any ingenuity, device, or detail that will save a fractional part of a second may represent a substantial percentage increase in the efficiency of operation. For instance, communication is very important in a large plaza and a matter that is sometimes overlooked. The toll lanes and the supervisory office should be connected with a two-way amplified intercommunication system.

A general observation on architectural treatment might also not be amiss here. A toll plaza is an obstruction on the highway, and, in the interest of promoting traffic movement, the architectural treatment should be such as to minimize the obstruction effect. Within the limitations imposed by structural and functional adequacy, every effort should be made to design on slender lines. This is particularly important for the onside plaza where the close spacing of booths presents a problem in overcoming the claustrophobic effect mentioned elsewhere. The tollgates are not the place for "fortress" type of architecture intended to reflect the solidity of the enterprise.

PUBLIC RELATIONS AND ECONOMICS

The purpose and premise of the modern express highway, and particularly the toll highway, is the movement of large volumes of traffic with dispatch, freedom from congestion, and safety. On the toll facility, the toll plaza is an obstruction to traffic, necessitated by the method of financing. It is inherent in the operation of a plaza that traffic shall be at least momentarily delayed. It is imperative that the delay encountered shall be a minimum consistent with the completion of a toll transaction. Insofar as the patron is concerned, his impression of the efficiency of the toll facility will be measured in large part by his relative freedom from delay and inconvenience encountered in the toll plaza. Generally the standard of delay and inconvenience acceptable to the patron requires that the plaza operate at a level lower than the maximum capacity of the plaza in terms of the volumes of vehicles handled. Each toll transaction is a public contact and it is highly desirable that the impression created in this contact reflect creditably on the facility. In itself this establishes a warrant for designing the plaza on the basis of generous capacity.

Tollgate construction is relatively costly and therefore should not be overdesigned. Nevertheless, if the traffic is available to warrant the provision of a toll lane, it will be found that the cost of the lane is a comparatively minor percentage of the total cost of operation. The money involved in the construction of a single lane as a unit will vary over quite wide limits, depending on the conditions encountered and the facilities provided. Discussion of the economics of toll-lane construction would therefore be rather idle without detailed information on the specific controlling conditions.

On the Bay Bridge, the cost of constructing and equipping an average lane is about \$30,000. The cost of other construction that could properly be chargeable to the unit cost of the lane, such as office and employee housing, general lighting, extra roadway required in the transition area, etc., would probably double this cost, or say \$60,000 per lane.

On the basis of handling a million vehicles per year per lane and writing off the investment on the basis of capital recovery in 20 years at 4 percent interest, and with a reasonable allowance for maintenance, the cost per vehicle would be just about 0.5 cent. Our present operation cost, exclusive of capital charge, is 2.24 cents per vehicle. Thus, in round figures, the cost of toll facilities in this instance is 18 percent of the total operation cost. A large variation in toll lane cost would reflect a much smaller percentage cost in total operation expense. The patron confronted with delays at the plaza because of inadequate facilities is not likely to be happy with the knowledge that his delay is saving a fractional part of a cent on the cost of handling his journey.

CONCLUSION

This paper is written to present some information and conclusions on a subject that is important in the current highway picture but has been largely neglected in our technical literature. While it is hoped that the content of the paper will in itself have value to other engineers, it is necessarily limited to experience encountered in specific facilities. It will have served its purpose if it encourages others in the same field to present their experience on that important and unique feature of the toll highway facility—the tollgate.