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REFERENCES

1. R.B. Wong. Golden Gate Bridge Toll Plaza Master Plan Study. Ammann and Whitney, New York, 1982.
2. B.C. Greenshields, D. Shapiro, and E.L. Ericksen. Traffic Performance at Urban Intersections. Bureau of Highway Traffic, Yale Univ., New Haven, CT, Tech. Rept. 1, 1947.
3. W. Kunzman. Another Look at Signalized Intersection Capacity. ITE Journal, Vol. 48, No. 8, Aug. 1978, pp. 12-15.
4. C.E. Clark. The Greatest of a Finite Set of Variables. Operations Research, Vol. 9, 1961, pp. 145-162.

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Abridgment

Tandem Toll Collection Systems

LOUIS D. RUBENSTEIN

By using two or more collection stations in the same traffic lane, tandem toll or parking-fee collection increases lane capacity and reduces the need for plaza widening. Data are presented relating processing rates to toll fee; e.g., the rate for a $1.25 fee is 30 percent slower than that for a $1.00 fee. Toll agencies that have implemented $1.25 tolls have encountered extreme congestion, especially with the weekend recreational traveler. Several operational configurations of tandem tolls are described. A coordination device is described to automate the control of motorist traffic signal and payment signal to distinguish between axle registrations of successive vehicles, even under dense conditions. Slow collection devices such as paper-money acceptors or flexible-ticket readers that are impractical at a conventional active lane are feasible in tandem. The expected capacity increase depends on the conventional cycle time, its standard deviation, and the distance between the toll stations. When the distance is several vehicle lengths, the stations are buffered, which results in better performance and independence of capacity increase on cycle time variance. The slower the existing collection time, the greater the capacity increase, e.g., 6 s/vehicle yields a 34 percent increase, 20 s/vehicle, 1.75 percent increase, when buffered.

There is a growing need for measures such as tandem toll booths to rapidly increase the traffic capacity of existing toll plazas. The experience at the Golden Gate Bridge and the Triborough Bridge and Tunnel Authority with long queues when toll rates were raised to more than $1 can be expected to be repeated at other tollway facilities. The high inflation rate of the last several years, one-way toll collection, and the use of toll surpluses to subsidize mass transit operations are pushing many toll fees to above the $1 level.

Stop-watch surveys that I have conducted indicate the relative effect of the toll fee on the vehicle-processing rate; they are summarized in Table 1.

Many existing toll plazas were designed when traffic volumes were lower and vehicle-processing rates higher and are not equipped to accommodate fees of more than $1. As toll fees rise, the problem will become more widespread.

This approaching problem will remain for years. Efforts by the U.S. Treasury Department to popularize the use of a $1 coin have not been successful. Similarly, efforts by toll operators to promote use of high-value tokens have met public resistance and are not very effective with the weekend recreational traveler. Busy motorists are not willing to accept the inconvenience and advance payment requirements of token prepurchase without a substantial discount. Even a 10 percent discount for tokens will reduce the revenue of many facilities a greater amount than the total cost of the existing toll-collection system. Token discounts also increase opportunities for employee fraud.

New technologies such as automatic vehicle identification had offered potential for speeding toll processing, but after years of development they have still not overcome the operational, cost, and privacy obstacles to their widespread implementation. Toll-collection computerization programs have been directed at improved auditing capabilities and not improved traffic flow.

The patronage of toll booths in the outer roadway lanes is lower than that in the central lanes, even under congested conditions. The approach to a toll plaza must be widened gradually over a long distance, which increases construction and maintenance costs, particularly on elevated plazas. If there are heavy weaving movements due to the location of particular entrance/exit ramps, even long tapers may not be effective. Tandem lanes would also lessen air-pollution levels in the toll plaza.

Table 1. Effect of toll fee on processing rate.

Passenger-Car Fee ($)	Bridge Surveyed	Manual Lane-Processing Rate[a] (s/car) Sample Avg	Best Avg
1.20	San Diego-Coronado, California	10.0	9.1
1.25	Throggs Neck, New York City	9.8	9.0
2.00	Golden Gate, San Francisco, California	8.8	6.5
0.75	San Francisco-Oakland Bay, San Francisco, California	6.9	6.6
1.00	Golden Gate	6.4	6.1
0.40	Carniquez, I-80, Vallejo, California	6.3	5.9
0.25	Vincent Thomas, Long Beach, California	5.9	5.5

[a] Observations are based on 120 observations per bridge, under moderate traffic; survey was conducted in spring 1982 during hours when commuter carpool free-passage rates were not in effect. Plaza grades were zero to slight. Best averages exclude patrons with exceedingly long service times, apparently unrelated to the toll fee.

Table 2. Effect of processing rate on increase in capacity of tandem tolls.

Single-Station Toll Cycle Time (s/vehicle)	Application and Typical Fee	Increase in Capacity (%)	
		Two Toll Stations	Three Toll Stations
5.5	Single-coin toll, car	34	49
6	$1 toll, car	36	55
9.5	$1.25 toll, car; distance-related turnpike toll with ticket	54	89
14	Tractor-trailer	47	75
20	Time-related car parking fee with ticket	75	134

Estimates for an increased traffic capacity of more than 40 percent for tandem lanes are described in Table 2. These estimates are supported by actual experience. The New York State Thruway used tandem toll operations at major bottleneck toll plazas on several peak days per year for more than 10 years until plaza widenings were completed. In spite of the irregular use and makeshift, nonautomated coordination and accounting of the system, the Thruway Authority reports that tandem toll operations resulted in capacity increases of 25 percent. Los Angeles International Airport has used manually operated tandem parking-fee collection on peak days since October 1982; according to Bill Barnett, vice president of Parking Concepts, Inc., capacity increases of more than 50 percent have been reported. A demonstration of an automated toll station in tandem is planned on the Bronx Whitestone Bridge in the summer of 1983.

A recent study (1, p. 17) developed a model that describes the capacity increase available by tandem toll collection. The model indicates the importance of designing and operating the stations in a tandem toll lane so that delays in one booth are not communicated to the second booth.

A 40, 25, or even 15 percent increase in toll-lane capacity can have a tremendous impact on toll plaza queues. Application of standard queueing-analysis formulas (2, p. 364) indicates that in the situation where the vehicle arrival rate is 95 percent of the vehicle service rate, a 15 percent increase in the service rate will reduce the average queue length from 18 vehicles to 4 vehicles. At toll plazas with high traffic stream divergence angles, queue lengths as short as 9 vehicles can lead to blockage of access to the outer lanes and an unstable flow condition.

Early field tests with tandem tolls experienced difficulty with coordination of the consecutive toll booth activity and revenue accounting. Designs have been developed (U.S. Patent 3 686 627, August 1972) that electronically coordinate the traffic flow and revenue accounting and automatically adjust to patrons paying at the wrong booth. Auditing computers installed in modern toll plazas can implement these designs at minimal expense.

Tandem toll booths are most effective when used with automatic processing equipment or during peak hours or on peak days to provide supplemental capacity. By proper scheduling of operating shifts or use of manual and automated lanes in tandem, increases in operator costs can be minimized.

OPERATIONS GUIDELINES

Sequencing and Layout

To derive the full potential of tandem tolls, they must be applied in appropriate locations and in an effective manner. Several operations guidelines that can be identified at this time are described.

A typical two-direction toll plaza is shown in Figure 1. It is characterized by a tapered approach roadway. Such conventional toll plazas have a single line of toll booths crossing the roadway. Tandem tolls permit the central lanes to carry a higher volume, and less traffic needs to be processed in the outer lanes. Figure 1 shows a set of tandem toll booths installed in the central section of the plaza. The lengthened toll island and the second treadle indicate a tandem lane in the diagram. The islands provide a barrier that restrains each vehicle in its lane and also screens visual disturbance that can slow operations.

Any equipment used in a conventional toll lane could be used in a tandem lane. Tandem toll lanes make feasible the use of some equipment that might otherwise be too slow to install in an active lane, e.g., a $1 bill changer, stored-ride magnetic card reader, or at a parking lot exit a time-related ticket reader and fee collector. Several additional units of equipment are required in a tandem lane. Typical signs to instruct the motorist at which booth to pay are shown in Figure 2. In addition, a device to coordinate the activities of the two toll booths is desirable. Although less effective, manually operated and coordinated systems could implement tandem tolls on a temporary basis.

The coordination device must identify each vehicle as it travels through the toll lane and know whether it has or has not paid its toll. This is accomplished by keeping a tally of the differences in axle counts between treadles A1 and A2 in Figure 2. The sequence of axle counts and payment registrations detected at each station can be the basis of a system to automatically count and check the number of axles of each vehicle.

The device could be set to collect a toll from every other vehicle at each station or could use a different collection configuration. If a patron mistakenly pays at the upstream booth, the device memory will cause a proceed signal to occur when that vehicle reaches the downstream booth.

Alternative operational configurations for a tandem toll lane such as batch, alternate vehicles, synchronized stations, automatic-manual stations, three collection stations, and automatic truck classification are discussed elsewhere (3).

Plaza Width and Taper

Disadvantages of wide toll plazas that can be reduced by tandem tolls include increased right-of-way costs, relative lower activity of outer toll lanes, and unstable flow conditions caused when access to the outer toll lanes is blocked by queues.

Early toll plaza designers recognized the importance of minimizing toll plaza widths and employed techniques such as driver- and passenger-side toll-collection booths to increase the number of toll lanes in a given plaza width (4). With the increased popularity of bucket seats and as a result of operations research studies that noted driver reluctance to use the passenger-side motorist collection booths and their slower processing times, their use in toll plazas was discontinued (5).

The only quantitative evaluation of this driver reluctance available in the open literature pertains to the San Francisco-Oakland Bay Bridge (6, p. 137). An approximate 2.5 percent drop in traffic volume is reported to occur for each 1 percent increase in divergence.

To overcome this effect and to reduce accidents, several references recommend long toll plaza

Figure 1. Two-direction toll plaza with tandem tolls in central lane.

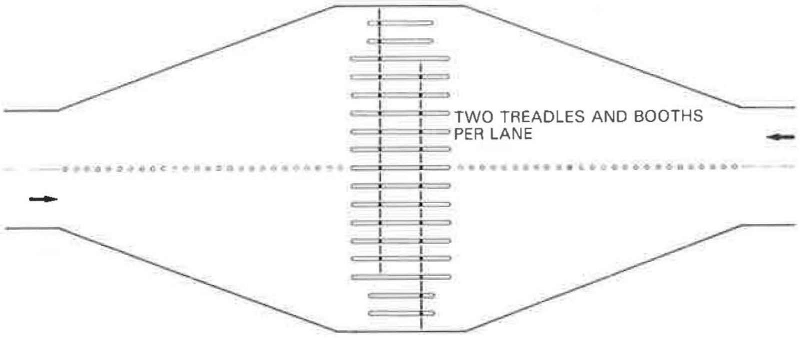
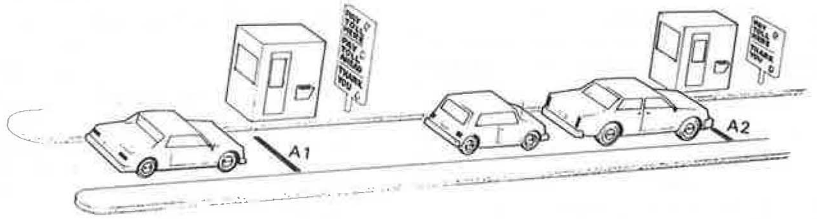


Figure 2. Motorist instruction signs in tandem lane.



tapers. Citing New York State Thruway standards, a report by the New York State Department of Transportation (7, pp. IV-4, IV-5) recommends a desirable taper of 20 to 1 and a minimum taper of 8 to 1. Below the latter value, it is stated that merging and weaving accidents will increase rapidly. Long tapers can be expensive in urban areas. A European study recommends a taper rate of 10 to 1 (8, p. 189). In addition, if the plaza taper is insufficient, turbulence caused by weaving and merging can cause the plaza to be the minimum-capacity section on the roadway. Several major bridges and tunnels have been built with inadequate tapers due to space constraints (9, p. 255). Inadequate tapers can also develop when toll plazas are widened to accommodate increased traffic.

The required taper rate can be estimated on the basis of its ability to prevent queues extending from the toll barrier from cutting access to the outermost toll lanes. The taper rate will depend on the expected queue length (QL) in front of the toll booth.

QL is given by (2)

$$QL = [\rho^2/(1 - \rho)] \text{ (number of vehicles)} \quad (1)$$

$$\rho = \text{(toll lane arrival rate)/(toll lane service rate)} < 1 \quad (2)$$

For example, if service rate is 1/(6 s•vehicle) and arrival rate is 1/(8 s•vehicle), ρ is 0.75.

For a vehicle of width CW to move from behind the queue to the adjacent outermost lane, a lateral distance along the roadway of TPR*CW is required, in which TPR is the taper rate.

If LW is the lane width, then by definition of taper rate the minimum lateral approach roadway is TPR*LW. The queue length plus the minimum car lane-change length must be less than the approach roadway length.

$$QL*VS + TPR*CW \leqslant TPR*LW \quad (3)$$

$$TPR \geqslant (QL*VS)/(LW - CW) \quad (4)$$

By using VS = 25 ft, LW = 15 ft, and CW = 6 ft, TPR = 2.77QL. Corresponding values of ρ, QL, and TPR are indicated below.

ρ	QL	Taper Rate
0.95	18	50/1
0.90	8	22/1
0.85	4.8	13/1
0.80	3.2	9/1

The above shows the sensitivity of the plaza design guidelines to the toll processing rate. Most toll plazas during peak hours will have queues of at least five vehicles.

INCREASE IN CAPACITY OF TANDEM TOLLS

If the tandem toll-collection stations are separated by a buffer distance of several vehicle lengths, the capacity increase is (3)

$$ICAP = 2\ [TC/(TC + TM)]\ 100 \quad (5)$$

where TC is the cycle time per vehicle in a nontandem system (e.g., 9 s/vehicle corresponds to a capacity of 3600/9 = 400 vehicles/h) and TM is the move-up time, or time between when the paying preceding vehicle leaves the toll station and when the nonpaying following vehicle reaches the same point at the toll station.

High, intermediate, and low estimates of TM are 3.2, 2.8, and 2.4 s/vehicle. These estimates are based on analogies to velocity profiles of vehicles entering a signalized intersection after the aspect changes from red to green and from a study of the on-time duration of the braking lights of vehicles as they stop at a toll booth after approaching through a short queue (3).

If the collection stations were not buffered, the increase in capacity can be estimated by (2, p. 364)

$$ICAP = 2\ \{TC/[TC + TM + 0.4SD\,(TC)/\sqrt{N}]\,\} \quad (6)$$

where SD(TC) is the standard deviation of the cycle times and N is the number of vehicles per batch if a batch-processing scheme is used.

Hall and Daganzo (1) present data collected at the Golden Gate Bridge and use the previous equation to calculate a capacity increase of ICAP = 18 percent for the $1.00 toll by using TM = 2.7 s and assuming that the booths are not buffered. When the booths are buffered, ICAP = 34 percent.

The result is consistent with a test of tandem tolls conducted at the Golden Gate Bridge in 1969. By using a makeshift arrangement where the second toll collector stood out in front of the islands, the flow rate was increased from 625 to 725 vehicles/h (16 percent) (2, p. 364).

Tandem tolls could also be used in a truck toll lane. Cycle component times for a tractor-trailer truck are TC = 14 s and TM = 7.5 s (8, p. 189).

The tandem move-up in time can be estimated as TM = 5.0 s.

The effectiveness of tandem tolls increases as the toll-collection cycle time increases. The previous equations were applied to derive Table 2.

APPLICATION TO REDUCE NEED FOR PLAZA WIDENING

I have presented an example that illustrates one of the situations in which a tandem toll system would be more economical than additional conventional toll lanes for increasing a toll plaza's capacity on weekends (3).

The cost parameters in the example are as follows:

1. Capital cost per additional booth:

Item	Cost ($000s)
Toll booth	40
Toll registry equipment	30
Tapered approach road (1500 ft)	1500
	1640

2. Present worth of staffing: half-day/week, $60 000.

By using these parameters, the capacity increase per unit of cost is

1. Tandem: 1.6 cars/(h•$1000) and
2. Conventional: 0.6 car/(h•$1000).

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REFERENCES

1. R. Hall and C. Daganzo. Tandem Toll Booths for the Golden Gate Bridge. Institute of Transportation Studies, Univ. of California, Berkeley, Res. Rept. UCB-ITS-RR-82-7, 1982.
2. M. Wohl and B. Martin. Traffic Systems Analysis for Engineers and Planners. McGraw-Hill, New York, 1967.
3. L. Rubenstein. Tandem Toll Collection Systems. Aug. 1982 (available from the author).
4. J.F. Curtin. Bridge and Tunnel Approaches. Proceedings of the American Society of Civil Engineers, 1940, p. 1821.
5. L.C. Edie. Traffic Delays at Toll Booths. Journal of Operations Research Society of America, Vol. 2, No. 2, May 1954, p. 121.
6. H.C. Wood and C.S. Hamilton. Design of Toll Plazas from the Operator's Viewpoint. HRB, Highway Research Board Proc., Vol. 34, 1955, pp. 127-139.
7. Final Report: Engineering, Environmental, and Socioeconomic Reevaluation of State Implementation Plan Strategy B-7: Tolls on East and Harlem River Bridges. New York State Department of Transportation, Albany, April 1977.
8. G. Roemer. The Design and Operation of Toll Booths. Oesterreichische Ingenieur Zeitschrift, Vol. 13, 1978, p. 189.
9. D.R. Culverwell, Freeman, Fox and Partners. Some Aspects of Toll Systems for Major Bridges and Tunnels. Planning and Transportation Research and Computation Co., London, England, 1974.

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Reliability of Classified Traffic Count Data

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The reliability of classified traffic count data collected for the planning and operation of highway systems is examined. Manual classified count data are subject to serious errors, whereas automatic vehicle classification with modern microprocessor technology may have other accuracy problems. Accuracy checks carried out in the United Kingdom are described for two automatic classification systems—for simple classification by using inductive loops alone and for detailed classification by using loops and axle detectors in combination. An evaluation of automatic classification equipment, including these simple and detailed systems, has been carried out in the United States by the Maine Department of Transportation. The results of these studies are described. The accuracy of simple vehicle classification based on vehicle length alone is limited by the fundamental properties of inductive-loop sensors. However, at sites with good lane discipline, the accuracy of classification is likely to be sufficient for most routine purposes such as the measurement of passenger-car-equivalent flows. Tests in the United States have shown that the reduced reliability of pneumatic-tube sensors leads to poor classification accuracy when these sensors alone are used for vehicle detection. More detailed vehicle classification methods can give greater accuracy, in excess of 90 percent, but as traffic conditions deteriorate, accuracies reduce. In the detailed classification method, there are difficulties in discriminating between certain cars, vans, and trucks, particularly where lane discipline is poor. Further developments of automatic classification techniques are currently in progress, and improvements are anticipated under urban traffic conditions and in the portability of detailed classification equipment. However, simple classified counters are already available and already have a part to play in displacing unreliable manual counts. Future trends in labor and microprocessor costs are anticipated to be such that as new developments become available, their rapid exploitation will become increasingly attractive.

Classified traffic counts have been carried out for decades to provide basic information used in the de-