ACKNOWLEDGMENT

We would like to thank Ron Gordon for suggesting the idea of tandem toll booths and for funding data collection. The Golden Gate Bridge Authority is thanked for providing data and for their overall cooperation. The theoretical aspects of this research were supported by the National Science Foundation.

REFERENCES


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 place 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 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 purchase 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.

<table>
<thead>
<tr>
<th>Passenger-Car Fee ($)</th>
<th>Bridge Surveyed</th>
<th>Manual Lane-Processing Rate (s/veh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.20</td>
<td>San Diego-Coronado, California</td>
<td>10.0</td>
</tr>
<tr>
<td>1.25</td>
<td>Throgs Neck, New York City</td>
<td>9.8</td>
</tr>
<tr>
<td>2.00</td>
<td>Golden Gate, San Francisco, California</td>
<td>8.8</td>
</tr>
<tr>
<td>0.75</td>
<td>San Francisco-Oakland Bay, San Francisco, California</td>
<td>6.9</td>
</tr>
<tr>
<td>1.00</td>
<td>Golden Gate</td>
<td>6.4</td>
</tr>
<tr>
<td>0.40</td>
<td>Carquinez, I-80, Vallejo, California</td>
<td>6.3</td>
</tr>
<tr>
<td>0.25</td>
<td>Vincent Thomas, Long Beach, California</td>
<td>5.9</td>
</tr>
</tbody>
</table>

*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.
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 booths 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).
tapers. Citing New York State Thruway standards, a
report by the New York State Department of Transport­
ation (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 insuffi­
cient, 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.

\[
QL = \frac{p^2}{(1 - p)} \quad \text{(number of vehicles)}
\]
\[
\rho = \frac{\text{toll lane arrival rate}}{\text{toll lane service rate}} < 1
\]

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

For a vehicle of width \( CW \) to move from behind the
queue to the adjacent outermost lane, a lateral dis­
tance along the roadway of \( TPR \times CW \) 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
\( TPR \times LW \). The queue length plus the minimum car lane­
change length must be less than the approach roadway
length.

\[
QL \times VS + TPR \times CW < TPR \times LW
\]
\[
TPR > \frac{QL \times VS}{(LW - CW)}
\]

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

<table>
<thead>
<tr>
<th>( \rho )</th>
<th>( QL )</th>
<th>( Taper Rate )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.95</td>
<td>18</td>
<td>50/1</td>
</tr>
<tr>
<td>0.90</td>
<td>8</td>
<td>22/1</td>
</tr>
<tr>
<td>0.85</td>
<td>4.8</td>
<td>13/1</td>
</tr>
<tr>
<td>0.80</td>
<td>3.2</td>
<td>9/1</td>
</tr>
</tbody>
</table>

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)

\[
ICAP = \frac{2}{TC/(TC + TM)} \times 100
\]

where \( TC \) is the cycle time per vehicle in a nontan­
dem system (e.g., 9 s/vehicle corresponds to a ca­
pacities of 3600/9 = 400 vehicles/h) and \( TM \) is the
move-up time, or time between when the paying pre­
ceding 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)

\[
ICAP = \frac{2}{TC/(TC + TM + 0.4SD(TC)/\sqrt{N})}
\]

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 \((3, p. 189)\).

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 \((2)\).

The cost parameters in the example are as follows:

1. Capital cost per additional booth:

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost ($000s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toll booth</td>
<td>40</td>
</tr>
<tr>
<td>Toll registry equipment</td>
<td>30</td>
</tr>
<tr>
<td>Tapered approach road (1500 ft)</td>
<td>1500</td>
</tr>
<tr>
<td></td>
<td>1640</td>
</tr>
</tbody>
</table>

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).

ACKNOWLEDGMENT

This report was supported by individual contributions of time, services, and a small amount of funds. No government or institutional funding was used. Several persons made noteworthy contributions: Linda Rubenstein for her encouragement and assistance in data collection; Ron Gordon, Redwood City, California, for supplying his collected information on tandem tolls; Nicolai Bellisi, Urbanit Associates, for his observations and special surveys; and Mel Kohn of Parsons Brinkerhoff, for his review of the early drafts of this report.

REFERENCES


Publication of this paper sponsored by Committee on Traffic Flow Theory and Characteristics.

Reliability of Classified Traffic Count Data

PETER DAVIES and DAVID R. SALTER

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 types of vehicles, 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-