MEASURING TIME LOSSES AT HIGHWAY BOTTLENECKS AND EMPIRICAL FINDINGS FOR THE CHESAPEAKE BAY BRIDGE

Richard J. Agnello, Department of Economics, University of Delaware

In this paper a readily implementable procedure is developed for measuring the length of traffic queues and time losses from severe highway congestion. The method is then applied to an actual situation where congestion is so great that 2-lane traffic backups several miles in length are formed. Time losses are calculated for past observations and forecast for future years. Although time loss is a crucial element in highway investment analysis, little attention has been directed to the development and the comparison of alternative measurement techniques. In addition, there are few instances in traffic queuing literature where sophisticated measurement procedures are illustrated with real-world data. In general, the experience of the author has been that where sophisticated mathematical models are used the data are hypothetical and where real data exist the techniques used are deficient.

•THE evaluation of highway improvements must give special attention to benefits accruing in the form of time savings. It has been argued and empirically measured by the author that upwards of 90 percent of relevant benefits from highway investments may take the form of time savings (1; see also 5). A readily implementable procedure for measuring and valuing time savings is thus of crucial importance in highway investment decision-making. Although the value of time saved is by no means resolved (6), this paper is directed to the simpler question of how in practice to measure the time saved (i.e., in hours rather than dollars). This determination is thus a prerequisite to the final valuation of time savings and project evaluation.

In addition, the paper will focus on a single highway bottleneck rather than a complete network whose system interrelationships may be considerably more complex. For mathematical convenience the constricting bottleneck is assumed to occur at a point in space. An interval constriction such as a narrow length of highway does little to change the theoretical analysis, however, and is in fact the situation encountered in the empirical findings that follow.

The question addressed is thus how to measure effectively highway congestion time losses when the losses are so great as to cause queuing. The main elements of the measurement involve determining the number of vehicles affected by the congestion (i.e., the queue) and the interval and amount of the time constraint. Average delay is also investigated because the value of travel time may be sensitive to time loss per vehicle.

ARRIVAL AND CAPACITY APPROACH

An intrinsic approach to traffic queue estimation might relate traffic inflows (arrivals) and outflows (capacity) in order to determine those vehicles caught in the bottleneck at a given time. If continuous functions are assumed, the number of vehicles congested at a point bottleneck is

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$$Q(t_1) = \int_{t_0}^{t_1} \left[A(t) - C(t) \right] dt$$

where $Q(t_1)$ is the queue measured in vehicles and $A(t)$ and $C(t)$ are the arrival function and outflow function (capacity) at time t respectively.

Given a smooth arrival function and constant outflow, Figure 1 shows their relationship to the queue function measured as the cumulative area between the $A(t)$ and $C(t)$ functions. The queue starts to form at t_0, is at a maximum at t_1, and ends at t_2. Areas X and Y are thus equal to each other and to the maximum queue length in vehicles.

A fundamental problem with the arrival and capacity approach is the general unavailability of data on both arrivals and capacity. Although parameters of alternative arrival probability distributions could likely be estimated, the application of these functions to specific cases would involve much effort and imprecision. For a discussion of the stochastic process approach see McNeil (4).

In addition to arrivals subject to wide variation and uncertainty, the capacity function itself is not so well behaved. One-way operations, for example, may be put into effect by attendants at the scene of a bottleneck. These not only change capacity greatly, but may be used in an unpredictable and unsystematic way by the authorities on the scene. [Interviews with attendants at the Chesapeake Bay Bridge indicate that decisions to begin and end one-way operations are made by using a flexible decision rule. When traffic backups exceed approximately ½ mile, one-way operations are placed in effect if traffic in the other direction is light. In 1967 there were as many as 9 one-way operations in one day, with some lasting almost an hour. Frequently long backups form in the direction that is stopped, necessitating correctional one-way operations for the direction of light flow.]

Another factor causing a variable capacity is the well-known result in traffic engineering that capacity (defined as maximum traffic volume) is obtained only when the traffic density is "optimal." The precise relationships between traffic speed, volume, and density are somewhat unpredictable, depending mainly on the size of the highway (number and width of lanes) and additional factors such as curves, grades, location, lateral barriers, and traffic lights. An excellent summary of the research done in this area can be found in the Highway Capacity Manual (2).

Typical relationships between traffic volume, density, and average speed are shown in Figure 2. The graphs indicate that, after an "optimal" density D_o, additional vehicles on the highway actually decrease the traffic volume passing over the road or through a bottleneck. Although a unique capacity can be defined for a particular facility (V_o), the actual volume passing through a bottleneck under congested conditions is not constant but also depends on the inflow; $A(t) - C(t)$ is usually a complex and discontinuous function whose integral is solvable only after making numerous simplifying assumptions.

QUEUE FUNCTION APPROACH

From the foregoing analysis it is observed that a procedure bypassing the improper intergral of $A(t) - C(t)$ will be easier and more accurate. Going directly to the length of traffic queues is such an approach and can be easily undertaken by field measurement or survey. The Chesapeake Bay Bridge, a 2-lane facility spanning the Chesapeake Bay at Annapolis, Maryland, was used for such a study. [A second bridge parallel to the existing one was opened in mid-1973 after this study was completed.] A survey of commercial establishments located various distances from the bridge on both sides of the Bay was taken to determine how severe congestion was on various days and at various times of day. More than 15 gasoline station, restaurant, and motel owners were asked (a) whether traffic ever backed up to their establishment, (b) when and how often, and (c) how long traffic remained queued up on the busiest days. Aside from some confusion over the precise meaning of traffic backup, most of those interviewed were able to answer the questions. Their answers showed remarkable consistency when compared with one another and with their respective distances from the bridge. In cases of discrepancy the lower estimate was taken because most of those interviewed, being in favor of a new bridge, would likely tend to exaggerate the problem. To increase accuracy and consistency of responses, only the days of worst congestion were asked for.

With an assumption of vehicles per mile per lane (175 vehicles, for example, allows around 30 feet for each vehicle and spacing), the length of the queue (in vehicles) was determined for any given time during the most congested days. The total waiting time for all vehicles for a given direction and day is simply

$$\int_{t_0}^{t_1} Q(t)\, dt$$

where $Q(t)$ is the queue function, t the time of day, and t_0 and t_1 the times when the queue begins and ends respectively. Average delay for a given queue period may be determined by dividing time loss by traffic volume. Queue lengths are shown in Figure 3. Points are connected by straight lines; dotted lines are hypothesized extrapolations where no data were available.

TIME LOSS CALCULATION

Adding together the areas under each curve yields the nucleus of waiting time or time lost (in vehicle-hours) by all traffic using the bridge on the busiest summer weekends in 1967. The actual calculation of time loss on the Chesapeake Bay Bridge involved two slight adjustments to the simple area under the queue functions. Since the areas represent the time loss from a bottleneck considered as a point instead of a range, the time lost while on the bridge (within the bottleneck) must be added to that lost waiting to enter the bottleneck.

The second adjustment is a subtraction accounting for the fact that all the time loss is not saved by eliminating congestion. Since it takes vehicles some time to cover the queue distance with no congestion, a subtraction must be made to obtain actual time savings. For the queue time loss adjustment it was first necessary to calculate the average queue length (AQL), in vehicles:

$$AQL = \frac{\int Q(t)\, dt}{\text{number of hours queue exists}}$$

The average queue distance is calculated in miles as

$$AQD = \frac{AQL}{\text{vehicles per mile}}$$

The time adjustment may thus be computed assuming some average speed (for example, conditions of free traffic flow with no congestion). The subtraction for the bottleneck distance is obtained directly when the range of bottleneck is known.

Based on the queue functions in Figure 3 and these adjustments, the time loss for the busiest summer weekend periods in 1967 was calculated. Table 1 gives these results for the 5 weekend congestion time categories.

In aggregating for the whole year it is necessary to decide which days qualify as the busiest days and what adjustments to make for days when less than maximum congestion existed. Losses during holidays and days of minor congestion where interference occurs but no queues actually develop must also be included in any actual time loss calculation. The results of all assumptions and adjustments for 1967 Chesapeake Bay Bridge data are given in Tables 2 and 3. It is readily apparent that the congestion problem is a severe weekend peak-load phenomenon, with most of the time loss occurring on the summer weekends. Since most of the time loss results from summer weekend queues, non-peak-period congestion is of little consequence in computing the yearly totals.

Figure 1. Arrival and outflow functions.

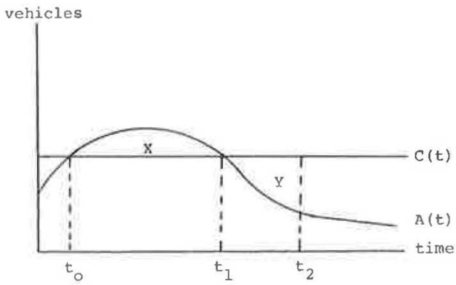

Figure 2. Volume, density, and speed relationships.

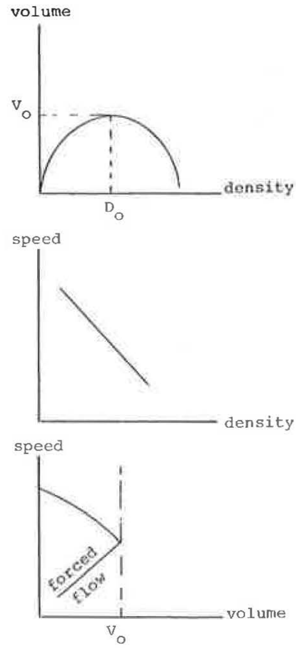

Figure 3. Queue functions for the Chesapeake Bay Bridge in 1967. Lines 1, 2, 3, 4, and 5 represent Friday eastbound, Saturday eastbound, Saturday westbound, Sunday eastbound, and Sunday westbound respectively.

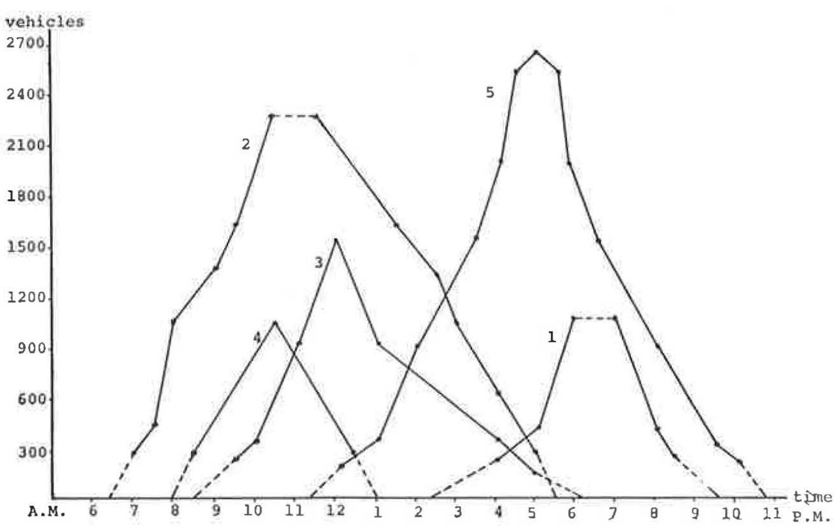

Table 1. Maximum summer weekend time loss.

Period and Direction	Total Time Loss (hours)	Average Time Loss[a] (hours per vehicle)	Peak-Period Average Time Loss[b] (hours per vehicle)
Friday eastbound	4,573		
Saturday eastbound	15,431	1.2	1.6
Saturday westbound	6,905		
Sunday eastbound	3,496		
Sunday westbound	14,334	1.0	1.7

[a]Average delay for all vehicles during the total queue period.
[b]Average delay for vehicles entering the queue at its longest.

Table 2. Total time loss for 1967.

Day	Time Loss (vehicle-hours)	
Holidays		17,246
July 4th period	1,390	
Memorial Day	540	
Labor Day period (2 days)	11,836	
Thanksgiving weekend	2,640	
Christmas and New Years	840	
Miscellaneous days		24,815
Summer weekends		507,909
Total		549,970

Table 3. Monthly time loss and traffic for 1967.

Month	Traffic Volume (thousands of vehicles)	Time Loss (hours)	Ratio (time loss per vehicle)
January	242	830	0.0034
February	197	690	0.0035
March	292	1,640	0.0056
April	324	1,180	0.0129
May	364	23,330	0.0641
June	498	120,450	0.2419
July	637	194,040	0.3046
August	604	144,900	0.2399
September	417	50,960	0.1222
October	344	3,450	0.0100
November	332	3,900	0.0133
December	293	1,600	0.0055
Total	4,544	549,970	0.1210

Source: Traffic volume obtained from the Maryland State Roads Commission.

Table 4. Predictions for traffic and congestion time losses during the May-September period.

Year	Traffic (thousands of vehicles)	Time Loss (thousands of vehicle-hours)
1967[a]	2,520	532
1967	2,578	
1968[a]	2,772	
1968	2,696 (5.4%)[b]	642
1972	3,336	1,046
1973	3,500 (4.9%)	1,150
1980	4,852 (4.3%)	2,001
1990	7,370 (3.8%)	3,588
2000	10,740	5,585

[a]Actual observations.
[b]Percentages in parentheses give annual compound growth rates between selected dates. Traffic grew at an annual rate of 6.3% during the 15-year observation period.

Calculation of the time loss for 1967 (a major part of the benefits if a wider bridge had existed for that year) is an intermediate step in determining the benefits from an expanded bridge investment. In order to predict time losses for future years, it is necessary to relate congestion to yearly traffic volume for more than one observation. Given traffic for a future year, the expected time loss can thus be calculated, and, alternatively, the time loss-traffic volume relationship helps to predict the future traffic demand itself. The association between the variables is two-way, with traffic volume dependent on many variables, including congestion. A multivariate traffic-demand regression model developed by the author (1) was used to generate the interdependent traffic and time-loss forecasts. These are given in Table 4.

CONCLUSION

This paper has attempted to develop and illustrate a simple and accurate technique for measuring time losses resulting from severe congestion in traffic queues. It is readily apparent from the empirical findings applied to the Chesapeake Bay Bridge that time saved by eliminating traffic queuing at bottlenecks may involve enormous magnitudes. For example, in 1980 over 2 million vehicle-hours would be saved by eliminating the congestion. It is hoped that the time-loss estimation technique developed will contribute toward a more refined measurement of a very important benefit component in highway investment decision-making.

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