Congestion Management Through Bus Metering at the Lincoln Tunnel

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The Lincoln Tunnel is a three-tube, six-lane tunnel connecting New York to New Jersey and is owned and operated by the Port Authority of New York and New Jersey. The tunnel provides weekday 3-hr p.m. peak service for approximately 22,000 vehicles, of which nearly 10 percent are buses. Bus traffic is concentrated in priority access lanes to avoid the general traffic peak congestion queues. The bus priority access lanes merge with selected lanes of general traffic near the tunnel's entrance portal. The resultant "bus-rich" traffic stream is turbulent, with an average throughput of 1,050 vehicles per hour; this stream consists of 350 buses and 700 cars per lane during p.m. peak hours. In 1993, the Port Authority conducted a test on fixed-rate access metering applied upstream of the bus and general traffic merge point at the New York entrance portal. The access metering investigation results showed a 15 percent increase in throughput, a 20 percent decrease in trip travel time, and a 20 percent reduction in the dispersion of 1-min flow rates (i.e., a more uniform traffic stream) with access metering, compared to unmetered access. The metered bus access lane was found to be a key factor in the experiment, since the bus drivers exhibited a high degree of compliance with the meter control. Their adherence fostered passenger car compliance, resulting in a smooth-flowing traffic stream. Extrapolation of the test results to the entire Lincoln Tunnel facility yields an increase in peak hour tunnel capacity of 1,000 vehicles per hour.

The Lincoln Tunnel is a three-tube, six-lane facility that provides access from New Jersey to midtown Manhattan (New York City). The facility is owned and operated by the Port Authority of New York and New Jersey. The Lincoln Tunnel was constructed in 1937 and consisted of a two-lane tube (now designated the center tube). The north tube was added in 1945, and the south tube was added 10 years later. The resultant complex services more than 110,000 vehicles on an average weekday, over 22,000 vehicles during each of the two daily 3-hr peak periods. The traffic mix at the tunnel is varied, with buses representing approximately 10 percent of the peak period vehicles. To facilitate mass transit, the tunnel management concentrates bus traffic in priority access lanes to allow them to bypass the p.m. peak congestion queues, which average 1,000 vehicles. Traffic in the bus priority access lanes from the Manhattan bus terminal merges with the general traffic flow in the outbound lanes near the tunnel's entrance portal. The resultant traffic stream tends to be turbulent with an average throughput of 1,050 vehicles per hour (vph), in the lanes used by buses. The traffic mix consists of 350 buses and 700 cars during these peak hours.

The congestion management strategy for general traffic utilizes the timely reversal of the center tube's traffic direction to optimally match the tunnel service to the existing demand. This management technique reflects due consideration of the aggregate, unserved demand that develops over the peak period and the availability of appropriate roadway on which the unserved queues may be stored.

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Utilization of the Lincoln Tunnel is asymmetric. The a.m. peak period is heavier in the Manhattan-bound (inbound) direction, and the p.m. peak travel period produces an increased outbound flow. As a result, the Port Authority's operating strategy for the facility provides four inbound lanes in the peak a.m. period and four outbound lanes in the peak p.m. period on normal weekdays. This reflects reversal of the center tube to meet the demand.

Congestion management at the Lincoln Tunnel reflects a strategy that includes priority service for mass transit vehicles and prudent choice of the approach roadways selected for storage of unserved demand. Bus access into the tunnel during the peak period is facilitated in the a.m. peak period by a contraflow lane on I-495 that permits bus access directly to the toll plaza, thus bypassing the general traffic queuing normally present during the a.m. peak. During the p.m. peak period, dedicated lanes allow direct egress from the Port Authority's Manhattan bus terminal to a merge point before the entrance portal of the tunnel's center tube. This arrangement permits priority service for buses, avoiding delays.

Aerial surveys of the Lincoln Tunnel indicate that the unserviced demand peaks at approximately 1,000 vehicles in both the a.m. and p.m. peak periods. In the morning, the Manhattan outbound flow is light, and significant queuing does not develop, even though only two outbound lanes are available. The delay due to congestion and queuing in the a.m. peak period is confined to inbound non-bus travelers. In effect, bus travelers are permitted direct access into the tunnel, whereas cargo and passenger vehicles must approach the tunnel through a regional network of roads and access lanes that serve to store the queues built up during the peak periods.

In the p.m. peak period, outbound travel is accommodated by reversal of the center tube at approximately 3:30 p.m. This action matches available capacity to the demand for service and minimizes the need for storage on the Manhattan street network and on the New Jersey road system. In the process, queuing during the p.m. peak period is directed to those roadways where adequate storage exists and reasonable congestion management techniques can be used. This mode of operation is maintained until approximately 7:00 p.m., when the peak demand for outbound service sufficiently subsides so as to permit reallocation of the tunnel complex to a configuration of three lanes in each direction. By that time, the unserved peak queue of approximately 1,000 vehicles begins to dissipate and the congestion subsides within about 30 min.

The capacity of the Lincoln Tunnel, as measured in passenger car equivalents (PCEs), is approximately 9,000 PCEs, with one bus or truck being equivalent to two cars. When this capacity is compared against the peak period maximum queue of about 1,200 PCEs, (1,000 cars and 100 trucks), it is apparent that the peak period queue is approximately equal to 13 percent of total hourly production capacity. Unfortunately, storage capacity requirements, congestion abatement principles, and the necessity of providing priority service for transit vehicles produces a situation in which significant queuing occurs in both New York and New Jersey. In effect, motorists seeking access to Manhattan through two lanes in the p.m. peak period experience delays of approximately 24 min under normal conditions. Furthermore, when multiple incidents are experienced during the early part of any peak travel period, the lost productivity contributes between 2 to 4 min of delay per incident per lane. Thus, on some occasions, the peak period congestion (and the associated delay) is twice the norm, and Manhattan-bound travelers may wait 50 min or longer before obtaining access to the tunnel.

In the late 1950s, Eddy and Foote conducted experiments in which access constraints at the Lincoln Tunnel produced throughput improvements of 7 to 10 percent. These early control experiments demonstrated the possibility of improving productivity through access control measures.

In 1993, the Port Authority commissioned Computran Systems Corporation to perform an evaluation study to determine the beneficial impacts that might be achieved from access metering. One phase of this program addressed the application of metering to the tunnel's bus traffic. The principle that motivated the study was that fluctuations in the normal traffic patterns at the Lincoln Tunnel tend to increase the dispersion observed in traffic flow and reduce the sustained average long-term productivity. In effect, metering was being investigated as a possible method of obtaining a more uniform input stream at the tunnel. The expectation was that a decrease in the dispersion (i.e., short-term flow rates) would result in an increase in the average total peak period productivity. The results of the experiment confirmed these expectations on a statistically significant basis for all measured variables.

CONTROL CONCEPTS

Preliminary studies conducted at the Lincoln Tunnel have revealed that the production rates observed in short-term measurements, (i.e., 1-min totals) often approached 1,800 PCEs per hour. However, the tunnel's sustained longer-term productivity (i.e., 15-min totals and greater), generally reflected throughput rates of 1,400 PCEs per hour or less. These data reflect the traffic mix, which consists of roughly one-third buses and two-thirds passenger vehicles at a production level of 1,050 vehicles per hour.

A metering experiment was designed to test the improvements in longer-term tunnel productivity. The site selected for evaluation was the tunnel's center tube, north lane. This roadway is served by two approach lanes: one provides direct access for buses exiting from the Port Authority's Manhattan terminal, and the other lane provides passenger vehicle access from the southern approach roadways that service the Lincoln Tunnel complex.

Metering signals were installed in two lanes with the intent of alternately metering buses and cars. An attempt was made to match the metering process to the underlying traffic mix of two passenger cars per bus. As a result, the metering practice adopted released two passenger vehicles for each bus released. The rate of metering was controlled by a personal computer host and was made adjustable from a baseline of 700 cars and 350 buses per hour (i.e., 1,050 vehicles per hour) to a peak rate of 900 passenger vehicles and 450 buses per hour (i.e., 1,350 vehicles per hour).

A schematic diagram of the control system layout on the approach roads to the center tube is shown in Figure 1. The placement of the traffic metering signals reflects the type of vehicles on which control is imposed and the need for a more homogeneous mixing of the two streams seeking access into the tunnel. For this reason, the metering rate for passenger vehicles was uniformly set at twice the metering rate for buses. The offset between the release time for buses and the release time for passenger vehicles was made field adjustable, so as to permit fine-tuning of the merge process.

OPERATIONAL ADJUSTMENTS

Transit vehicle metering was examined at various meter rate settings. It was observed that several days of familiarity with the signals were required before a reasonable level of bus driver compliance developed. Furthermore, the rate at which metering was set seemed to exhibit a resonance in compliance when the physical characteristics of the bus stream were best matched by the meter rate imposed. In effect, metering at a rate of approximately 400 buses per hour produced a smooth bus stream in which vehicles could coast to the meter signal, and thereafter accelerate smoothly through the merge point. Lower meter rates appeared to impose additional delay, which was objectionable to certain drivers, and higher rates produced a premature green indication. As a result, the metered bus stream seemed to flow most smoothly at approximately 400 buses per hour, even though a small percentage of the bus traffic involved articulating vehicles that took longer to pass the signal.

Compliance of the passenger vehicles to the metering signal was sporadic, compared to the compliance of buses. A substantial percentage of the passenger vehicles seemed unconcerned with the color of the signal when they approached the control point; some of this behavior continued even after the initial "training period" had passed. As a result, the smoothness of flow that developed in the bus stream was not apparent in the stream of passenger vehicles. However, the bus driver's adherence to the metering signal forced the passenger vehicles into a reluctant compliance. When certain passenger vehicles attempted to violate the right-of-way of a metered bus, the bus driver forced compliance by blocking the merge point. The results of the confrontation caused subsequent motorists to observe the metered signal. The smoothness of travel achieved by the bus traffic lane exceeded that of the passenger vehicle lane, but the ratio of buses to cars gaining access to the tunnel matched the metering ratio.

There was an apparent reduction in the size of the unserved queue of passenger vehicles that sought access via the metered lane. At first, this condition was attributed to shortfalls in the demand for service. However, in subsequent evaluation, the dissipation of queued demand was accounted for by the increased productivity that caused a corresponding reduction in the number of unserved motorists awaiting access.

Data collection was conducted over 24 separate p.m. peak periods. Twenty-five percent of these samples were measured without metering in effect. The remaining samples reflect approximately five meter rates in the range between 1,000 and 1,400 vehicles per hour.

The data was collected with a personal computer from vehicle detectors in each of the metered access lanes. Primary data were recorded at the time each vehicle detector was actuated and released. In effect, the time of arrival and departure of each sensed vehicle was recorded and stored on a computer disk for subsequent processing.

Analysis of the data was performed in a sequential fashion. First, the raw data were processed to generate 1-min flow rates in each metered lane. These data were compared to concurrent records of

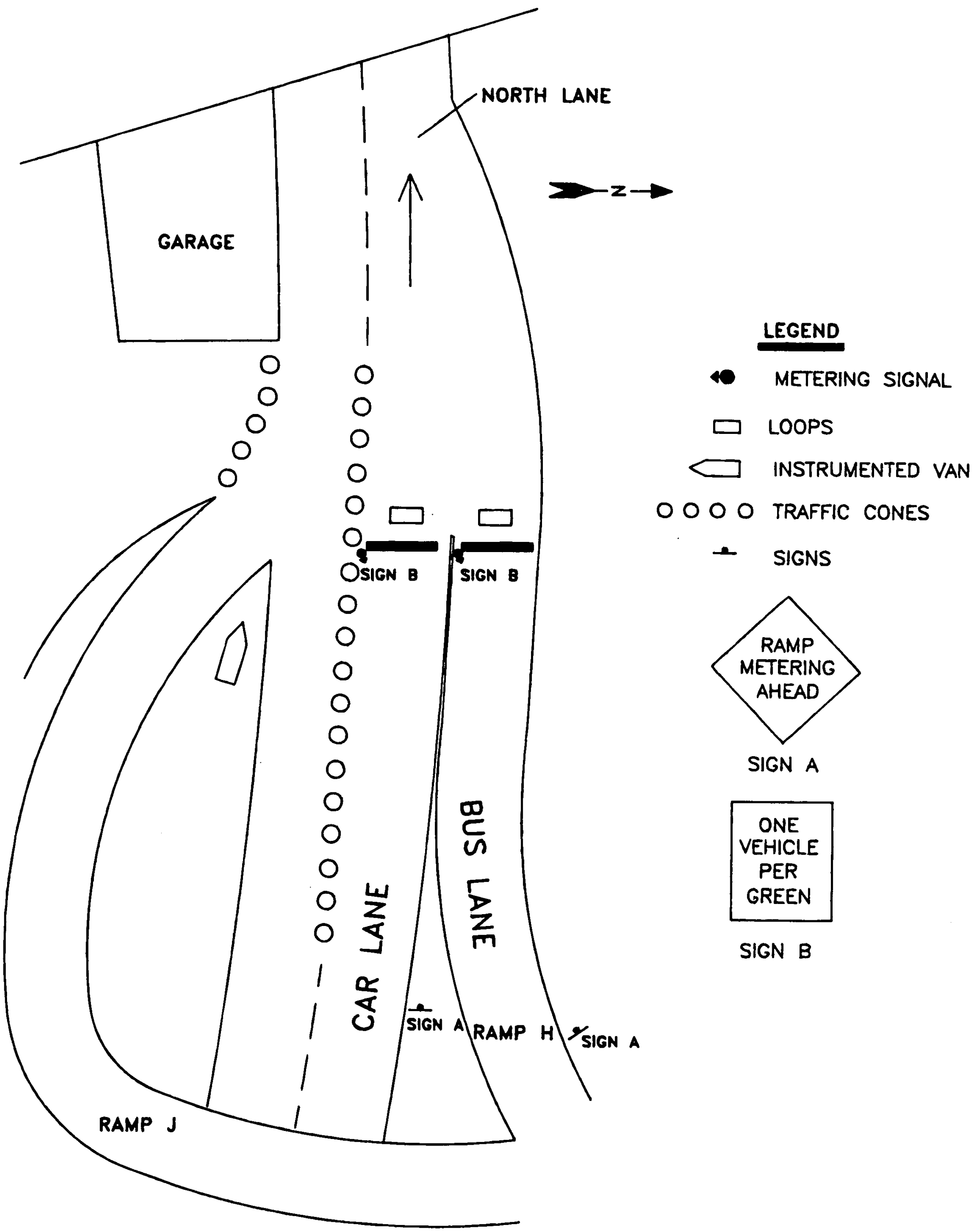

FIGURE 1 Schematic of test set-up at Lincoln Tunnel.

the signal indication to determine the actual per-minute metering rates that were displayed in each lane.

One of the principal variables of comparison was the average production rate achieved during the approximately 2-hr peak period that comprised each daily sample. These average production rates were compared with the average 2-hr peak period production rates achieved in the six unmetered samples.

FINDINGS

The results indicated that without metering, the average peak period production rate was approximately 1,050 vehicles. When metering was imposed, production rates of approximately 1,200 vehicles per hour were achieved. This translates into a production rate of approximately 1,400 PCEs through the tunnel's lane.

A quantitative comparison of the average peak period production rates is shown in Figure 2. On this graph, each test day's throughput is shown along with the respective meter rate in force that day. Additionally, the graph shows the upper and lower three-sigma boundaries of the unmetered throughput average. These data indicate that the average unmetered productivity is statistically different from each of the metered samples using a three-sigma confidence test criteria. In essence, the average productivity of the metered north lane of the center tube is statistically superior to the average productivity obtained without metering. The effect of the meter rate itself upon the observed performance is not discernible, and a linearized curve fitting of the data is relatively flat and approximately constant over the range of the examined meter rates.

As a second indicator of observed impact, the sequence of 1-min flow data was plotted as a function of time for each of the samples. A typical history obtained without metering is shown in Figure 3, and a typical pattern with metering is shown in Figure 4. Comparison of these records indicates two significant improvements. First, the average productivity with metering is greater than the average productivity without metering. Second, the range of variation in 1-min flow rates experienced without metering is significantly greater than the range of 1-min flow rates experienced with metering. In effect, metering increased the average productivity and decreased the dispersion in the throughput data. The result is a more uniform flow into the tunnel and a higher production rate through the tunnel facility.

Volumetric throughput is a key measure of tunnel productivity. It is the mark of the number of vehicles that were serviced through the facility. However, this measure of service quantity is only one of the principal indicators of improved performance. A service quality indicator was developed from measurements of the travel time experienced under both metered and unmetered conditions. A total of 6 sample days were selected for this analysis. Three of the sample days were metered days; the other three sample days reflected unmanaged operation, and were not metered. The study compared the travel time during the sample days to measure the impact of metering on the quality of service. The measurement of travel time was accomplished through the use of video camera recorders. Inflow and outflow at the tunnel was recorded concurrently throughout the 2-hr peak period. These video data were then reduced by the selective tracking of three identifiable vehicles that entered the tunnel in each of the twelve 10-min periods that comprised each 2-hr peak sampling interval. In effect, a total of 36 trip times, uniformly distributed over the 2-hr peak period, were used to measure service quality. The average and dispersion of trip time data were compared for each of the six selected samples. The result indicated a 20 percent decrease in the average travel time through the tunnel, and a decrease of 15 percent in the variation in peak period trip times when metering was imposed.

Analysis of the data clearly indicates that both the quantity and quality of service available with metering in operation were superior. Furthermore, the increase in the peak period throughput obtained with metering in effect reduced the delay experienced by queued motorists by reducing the number of queued vehicles and servicing the ones queued faster. Accordingly, metering produced an even greater beneficial impact on total travel time, since the waiting time to enter the tunnel and the time required to traverse the tunnel were both reduced.

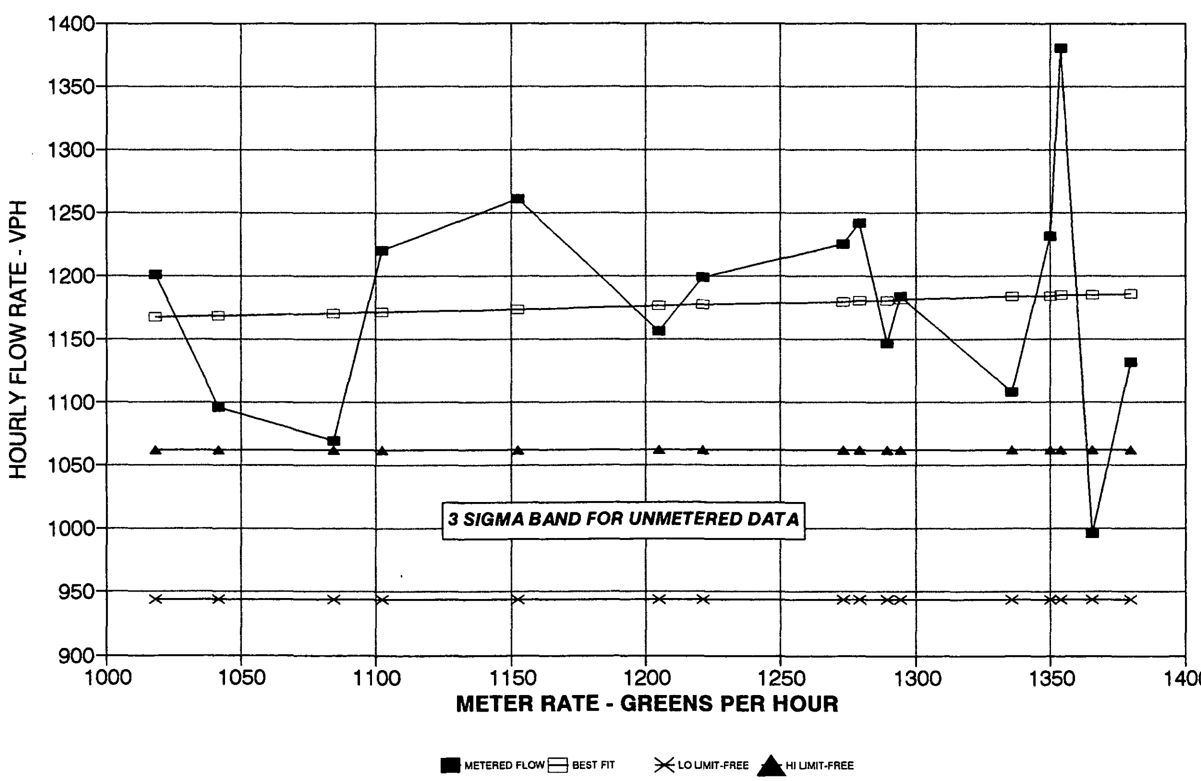

FIGURE 2 Hourly flow versus meter rate at Lincoln Tunnel.

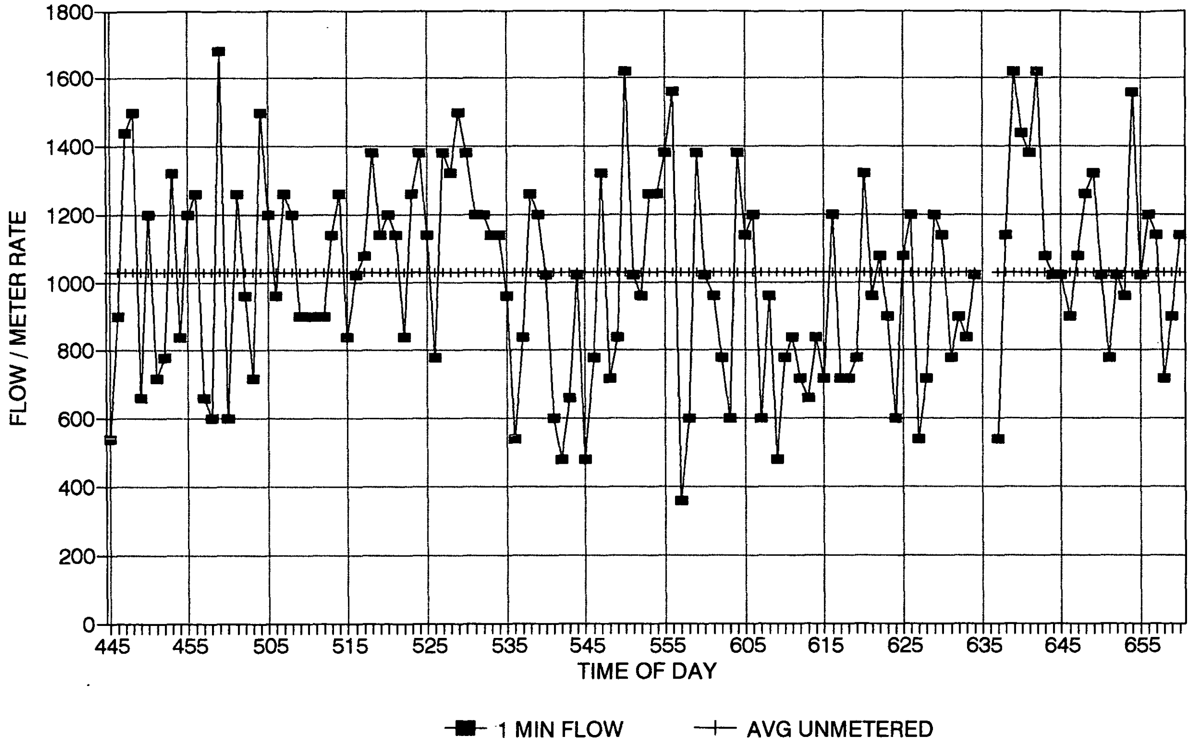

FIGURE 3 Unmetered 1-min flow rates at Lincoln Tunnel, November 24, 1993.

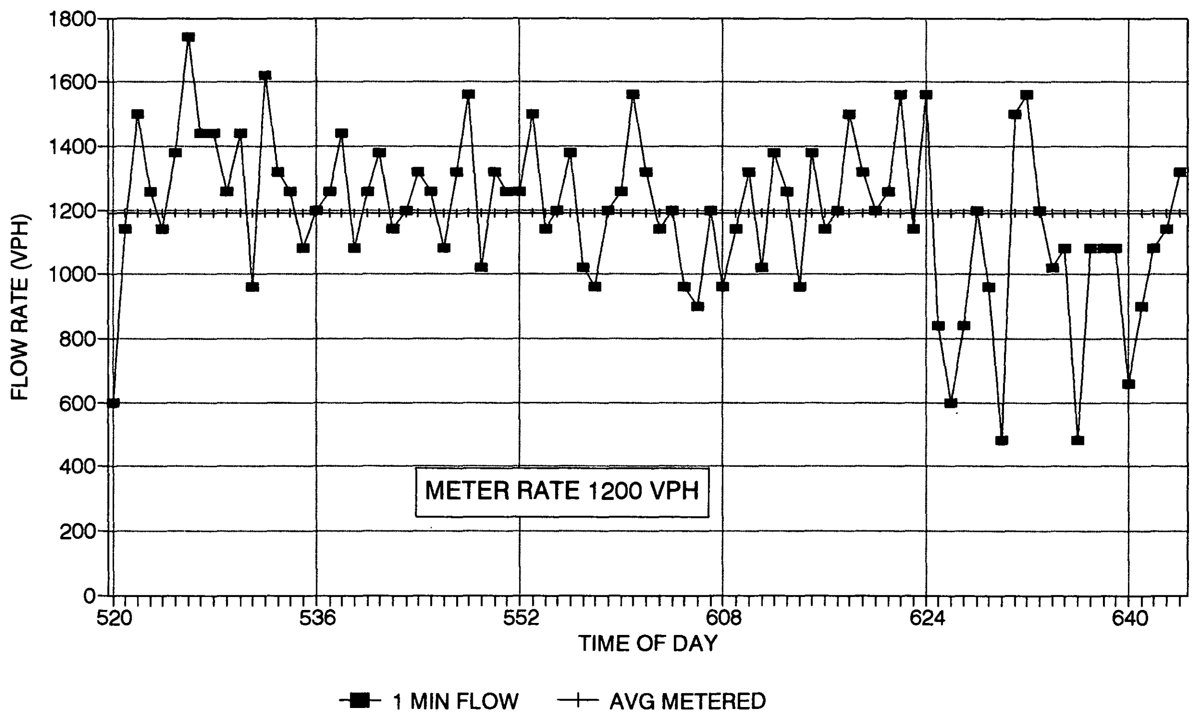

FIGURE 4 One-minute flow rates (vph) versus time at Lincoln Tunnel, November 29, 1993.

The total impact of metering at the Lincoln Tunnel is only partially reflected in the improved quantity and quality of service experienced by motorists exiting from Manhattan in the p.m. peak period. The metering of access into the tunnel reduces queuing of excess demand in New Jersey as well as in New York. In effect, increased throughput for New Jersey-bound traffic permits an earlier reversal of the center tube from the four-lane/two-lane mode to a balanced operation of three lanes in each direction. Acceleration of this reversal expedites the increase of the Manhattan-bound capacity by 50 percent (i.e., from two lanes to three) and significantly reduces the extent of congestion and the duration of peak traveler delay. Furthermore, extrapolation of these principles to the entire six-lane facility indicates that the increased productivity will match the present peak period demand. The effect of an improvement of this magnitude is significant relief of the peak period congestion that currently develops at both entrance portals of the Lincoln Tunnel.

CONCLUSION

The experimental program conducted by the Port Authority at the Lincoln Tunnel indicated that metering of mass transit vehicles improved the quality and quantity of service provided to these travelers and all other travelers who shared a common roadway. Thus, the impact of metering of transit vehicles was beneficial to all.

A representative sample of 400 buses that exit the Manhattan bus terminal in the normal weekday p.m. peak period carries between 12,000 and 16,000 passengers. In addition, passenger vehicles in the Lincoln Tunnel average approximately five people per four vehicles (i.e., 1.25 persons per vehicle). Therefore, the capacity of the Lincoln Tunnel was raised by approximately 2,000 travelers per hour through the use of access metering. In addition, peak period travel time was reduced in excess of 1 min for each of the travelers in the metered tube. This improvement corresponds to a savings of 250 person-hr of congestion delay each p.m. peak period. The annualized savings in gas consumption, air pollution, and other socially undesirable penalties complement this improvement in mobility.

The economic impact of improved tunnel productivity on the congestion experienced at the New Jersey side of the tunnel was not quantitatively assessed. However, if peak queuing approximates 1,000 vehicles each weekday p.m. period, and peak delay approximates 30 min, then the size of the peak p.m. period congestion that exists is on the order of 500 vehicle hours per day. With an average vehicle occupancy of 1.25 passengers, it can be projected that the magnitude of congestion experienced by motorists seeking service through the Lincoln Tunnel in both the a.m. and p.m. peak periods totals more than a quarter-million travel hours per year. All measures that reduce this avoidable delay are critical to the economic vitality of the region and warrant added investment in improving system performance. Consequently, the investigative team recommended moving forward on implementation studies of access control on all approaches to the Lincoln Tunnel.

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