Operational Effects of Automatic Ramp Control On Network Traffic

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•ONE of the major features of the National System of Interstate and Defense Highways is the physical control of traffic access provided by grade-separated interchanges. Traffic research by the Chicago Area Expressway Surveillance Project of the Illinois Division of Highways has indicated that further control of access may be needed, particularly in urban areas, to prevent or reduce congestion caused by traffic demands in excess of expressway operational capacity (1, 2).

To adjust entrance ramp traffic volumes to the available expressway capacity, the Project developed an electronic ramp metering device which automatically controlled the magnitude and rate of traffic entering an expressway. The first successful use of modified traffic signals to automatically meter one vehicle at a time onto an expressway was initiated in September 1963 at an entrance ramp on the outbound Eisenhower Expressway in suburban Chicago (3).

Extension of the ramp metering technique to three additional entrance ramps in June 1965 produced a continuous expressway control system 2.5 miles long, designed especially to reduce expressway traffic congestion caused by overloading a sensitive

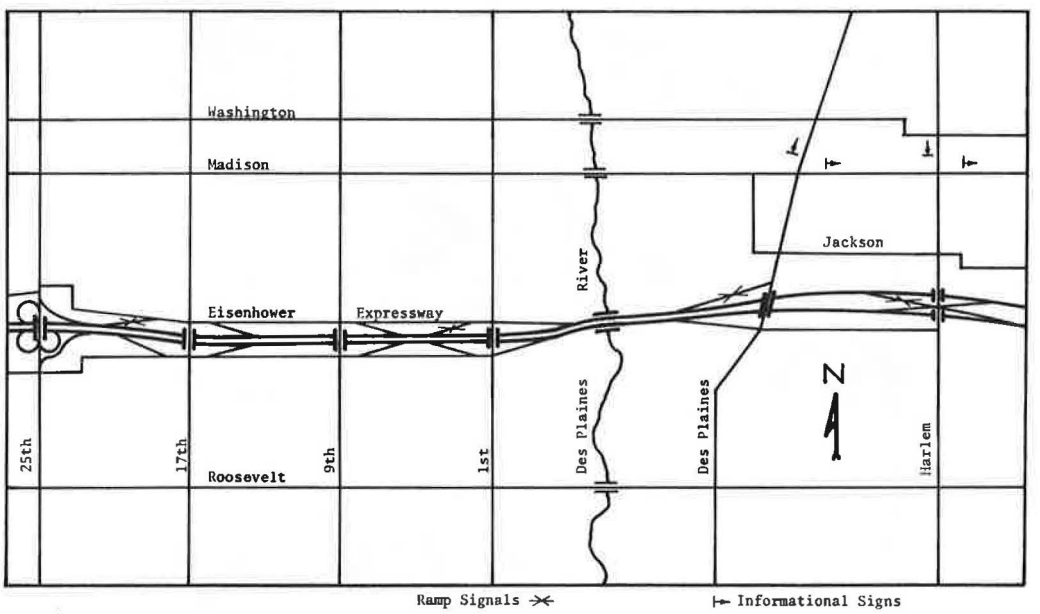

Figure 1. Locations of entrance ramp control signals and informational display signs.

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geometric section. As a supplementary measure, because ramp metering devices generate ramp queues and traffic diversion, four display signs were installed at strategic surface street locations to provide some expressway-bound motorists with advance advisory information concerning existing ramp and expressway traffic conditions.

This report summarizes the overall operational effects on both expressway and surface street traffic flow produced by the automatic control system of four entrance ramp metering devices and four supplementary informational display signs. The report by no means contains all the ramp control research findings produced by the Project, but highlights areas of special interest to freeway operating and research engineers.

CONTROL STUDY DETAILS

The pilot expressway control system consists of entrance ramp metering signals at four successive outbound (westbound) Eisenhower Expressway (I-90) diamond interchanges: Harlem, Des Plaines, First and 17th Avenues. The four supplementary informational signs are located on the southbound and westbound approaches to two major surface street intersections handling expressway-bound traffic (Fig. 1).

Equipment Characteristics

The modified (red-green) traffic signals which comprise each ramp metering device maintain a constant green indication in non-peak periods. During "rush" periods (3:30

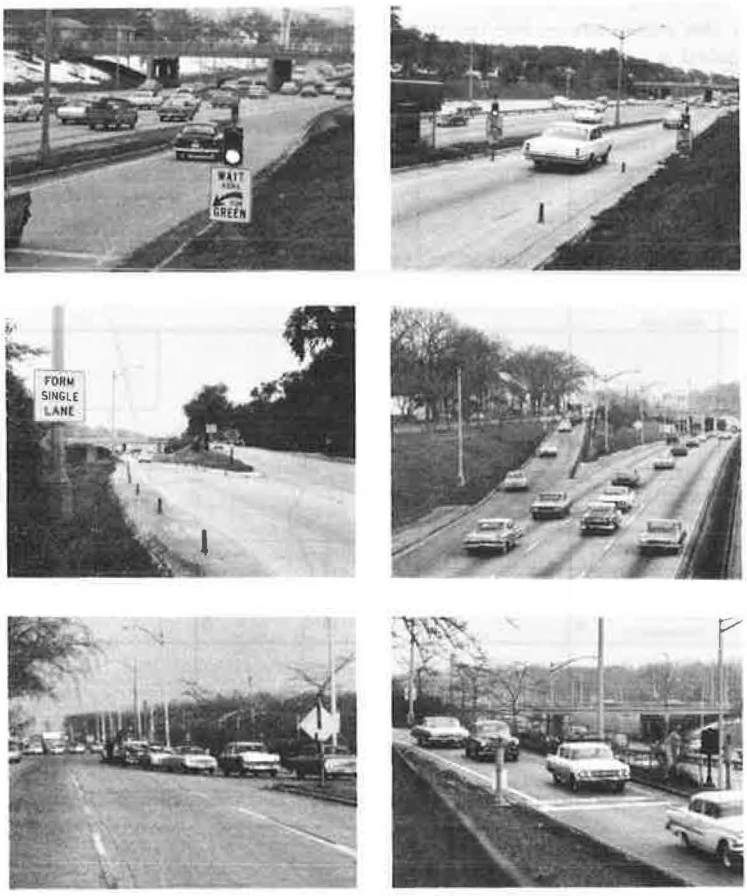
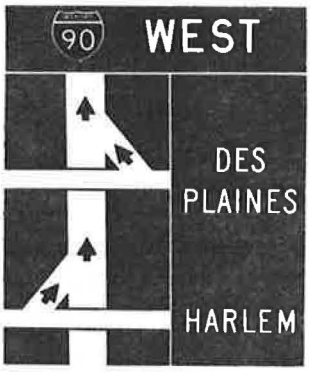


Figure 2. Ramp metering operations at First Avenue.



Westbound Madison
approaching Harlem

Southbound Des Plaines
approaching Madison

Figure 3. Informational display signs.

to 6:30 p.m. on commuting weekdays), the metering signals at each ramp rest in red and change to green for each ramp vehicle at minimum intervals ranging between 5 and 15 seconds. Thus, queued entrance ramp vehicles are released one-at-a-time into the expressway traffic stream (Fig. 2). Prevailing metering rates are automatically selected through a dectector-computer system which decreases entrance ramp flow rates

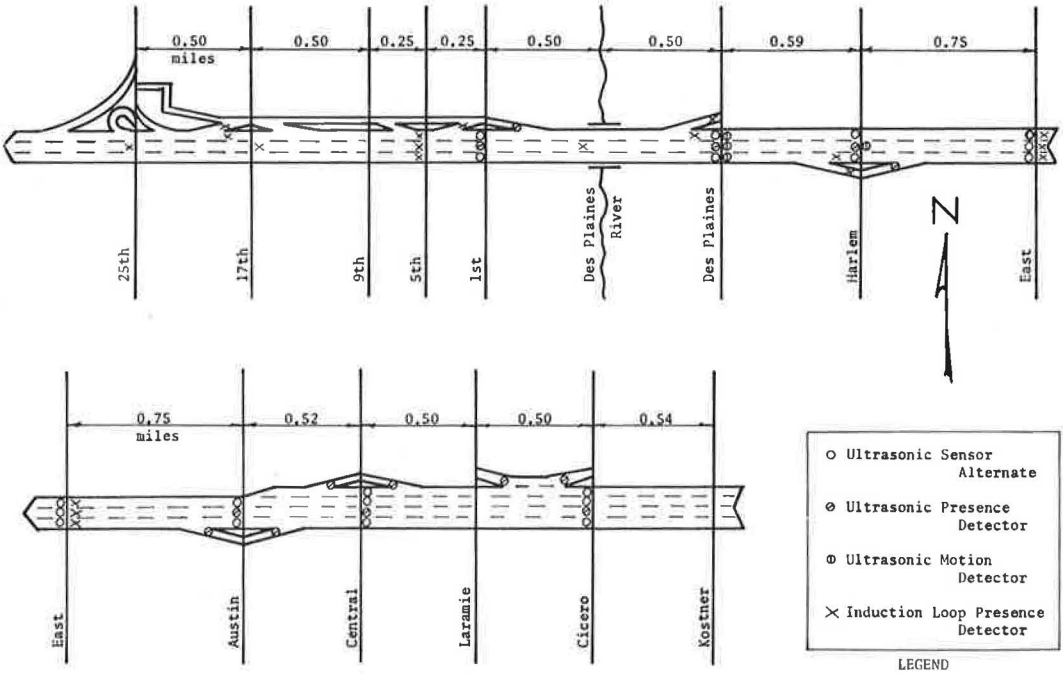


Figure 4. Electronic surveillance system on the westbound Eisenhower Expressway.

as measured expressway traffic conditions approach congestion levels (3, 4). Motorists disobeying red ramp signals trigger a violation alarm bell; signals of this type are enforceable under Illinois state law. Modified traffic signals of comparable appearance are in common use throughout the Chicago area at automatic toll collection stations.

To promote diversion to alternate routes when outbound expressway traffic conditions warrant, the supplementary informational signs display existing entrance ramp and expressway delays to some potential expressway users approaching or traveling on an arterial street serving as a major parallel expressway alternate. Each sign shows traffic conditions at the two nearest outbound expressway interchanges (to the west) by color-coded, changeable arrows: GREEN = NO DELAY; YELLOW = MODERATE; RED = CONGESTED (Fig. 3). If conditions at the nearest interchange are congested, motorists can use westbound Madison Street or other routes for travel to the next informational sign or to a more attractive ramp, thereby tending to decrease peak-period queuing behind ramp signals (5).

The ramp metering signals and supplementary informational signs are automatically controlled from continuous expressway and ramp traffic measurements. Since October 1962, expressway and ramp traffic has been monitored by an electronic detection system, which now covers a 6-mile outbound Eisenhower Expressway section between Cicero and 25th Avenues (Fig. 4). A total of 45 detectors provide inputs for the analyses of traffic operations on most ramps and at average expressway intervals of about ½ mile. A small, real-time, digital control computer and several analog computers in the Project office process detector data into system surveillance, control, and evaluation outputs (6). An office control console collates displays of expressway traffic conditions, prevailing metering rates, ramp signal changes and violations, sign conditions, and other information useful to the control observer.

Bottleneck Control Theory

The primary objective of the ramp control system is the prevention of expressway traffic congestion caused by overloading the three-lane Harlem Avenue to 17th Avenue section of the westbound Eisenhower Expressway. Should congestion develop despite ramp controls, or for reasons not attributable to entrance ramp turbulence, the secondary objective of the ramp control system is the restoration of non-congested traffic flow.

Each ramp metering device operates over the metering range from the maximum rate of 12 vehicles per minute (vpm) to the minimum of 4 vpm. As non-congested expressway flows rise towards maximum volume, the ramp flow rates are gradually decreased, thereby attempting to prevent the development of congestion from high ramp flow rates merging with high expressway flow rates. In the congested expressway situation, the minimum metering rate of 4 vpm is employed until non-congested operations return (3, 4).

The control section was selected to encompass the final outbound expressway bottleneck. A recurrent problem of traffic congestion existed east of the Des Plaines River bridge, where the otherwise depressed expressway rises to an at-grade cross section for passage over the Des Plaines River. The interplay of traffic demand and sensitive geometrics usually produced congested operations (from 4:30 to 6:00 p.m. each commuting day) which regularly extended upstream into the next major bottleneck, aggravating congestion where the expressway pavement reduces from four to three lanes (Austin Avenue).

Metering controls at the Harlem and Des Plaines entrance ramps were primarily intended to prevent bottleneck congestion. However, the sensitive geometrics in this area complicate the control problem. Peak-hour volumes of 550 vehicles per hour (vph) and 675 vph at the Harlem and Des Plaines entrance ramps, respectively, were loaded successively from the left and right sides of the expressway where a reverse curve, three closely-spaced overpass structures and a 3 percent upgrade decrease capacity.

Nevertheless, it was quite evident that Harlem and Des Plaines entrance ramp traffic often caused the introduction of congestion, whereas the geometrics were suspected of maintaining the congestion once it had developed. Although no overloading congestion existed anywhere downstream of the Des Plaines bottleneck, the downstream entrance ramp controls at First Avenue and 17th Avenue were deemed necessary to retain non-congested traffic flow west of the Des Plaines River bridge. It was anticipated that bottleneck improvements might increase flows through the downstream corridor and/or upstream ramp controls might divert traffic to downstream entrance ramps, thereby making it desirable to prevent the occurrence of congestion at locations previously trouble-free.

Evaluation Methods

Inasmuch as the ramp control system was expected to produce positive expressway benefits at the expense of some negative benefits on the contiguous surface streets and metered entrance ramps, the whole network traffic operations were analyzed for the 3:30 to 6:30 p.m. peak period before and after commencement of the ramp control system on June 21, 1965.

Expressway traffic measurements consisted basically of automatic digital computer loggings each minute of volume and occupancy for 36 detectors in the surveillance system. Manual expressway and ramp volume counts were used to supplement automatic detector data and to check detectors. Basic calculations of daily expressway performance were programmed to yield vehicle-minutes of travel time and vehicle-miles of travel. Individual travel-time samples were taken by matching license plates for certain-colored Volkswagens passing time-and-license plate recording stations. These travel times were utilized in one method of computing total travel time; an input-output technique, however, proved more efficient for data collection, analyses, reliability and accuracy (7).

Surface street traffic measurements were more difficult to obtain due to the permeable nature of a grid street system. Machine counters were employed to establish intersection approach patterns and to supplement manual intersection counts for 12 critical arterial intersections (8). Intersection approach delays (and entrance ramp queue delays) were estimated by recording the number of vehicles within a certain trap length every minute. Floating-car travel time runs were also made over numerous surface street routes.

EXPRESSWAY IMPROVEMENTS

Expressway operational measurements were recorded for 33 peak traffic periods both before and after the commencement of the ramp metering control system. Between 3:30 and 6:30 p.m. data were collected over a 5.40-mile expressway section from Kostner Avenue to 5th Avenue. Although the 2.59-mile East Avenue to 5th Avenue section comprises the basic control section, because traffic improvements over this distance could be directly attributed to the ramp control system, the longer data collection section extending back to Kostner Avenue was necessary to estimate the incremental control benefits occurring upstream at the Austin Avenue lane reduction bottleneck.

Extent of Congestion

A contour map showing the extent of expressway traffic congestion over time and distance was composed from the five best operational peak periods both with and without the ramp control system (Fig. 5). Congestion was defined as sustained traffic operations at reduced speeds, evidence by increased expressway lane occupancies accompanied by decreased lane volumes (volume-to-occupancy ratio less than 1.0).

Although the ramp control system did not completely eliminate congestion in the control section, both the severity and dimension of congestion were significantly reduced. The period of congestion on the Des Plaines upgrade was decreased 45 minutes (from 75 minutes to 30 minutes); the introduction of congestion was delayed by 35 minutes and recovery occurred 10 minutes earlier. The severity of congestion in the control section

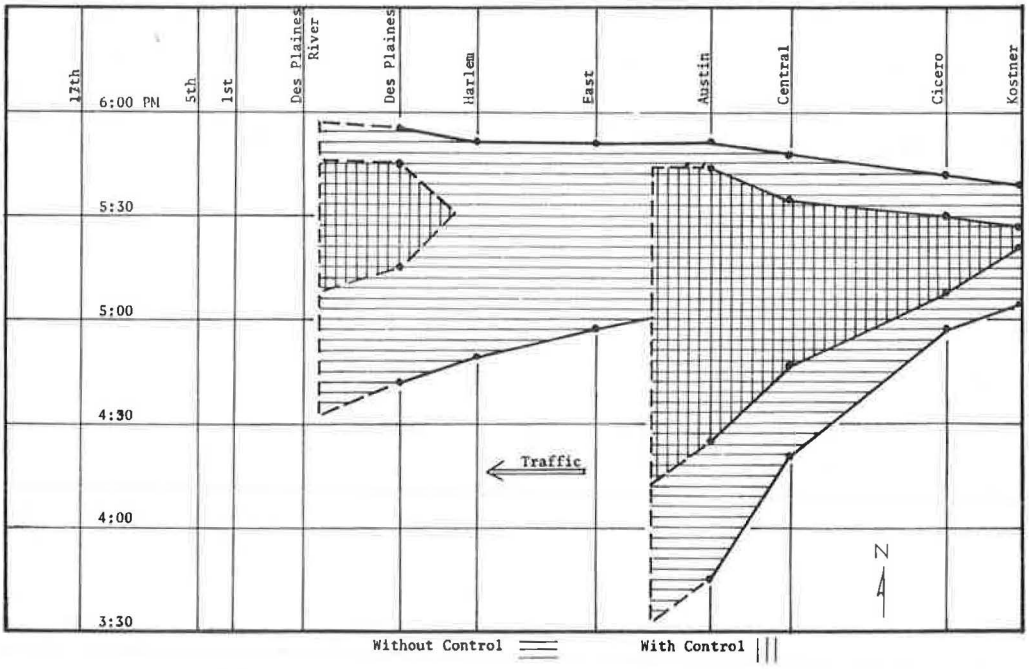


Figure 5. Expressway congestion contour map.

was reduced such that congested operations were confined to the immediate Harlem-Des Plaines area, a condition indicating expressway demands near the congested flow rate. As a result, the Des Plaines backup was prevented from influencing traffic operations at the upstream Austin bottleneck.

The improvements displayed at the Austin bottleneck, however, cannot all be assigned to the ramp control system, inasmuch as the "before" backup from the Des Plaines bottleneck did not compound Austin congestion until about 5:00 p.m. The changes east of Austin Avenue before 5:00 p.m., therefore, must reflect changes in traffic demand due to a redistribution of travel patterns and/or normal seasonal traffic variations. It should be noted in the contour map that congestion reductions were recorded well upstream. The improvements transmitted beyond the upstream data collection limits unfortunately went unmeasured, thereby lending a conservative tone to the measured changes.

Total Travel Time

The input-output technique for estimating total expressway travel time for all vehicles (the sum of all individual travel times) produces a plot of vehicles in the expressway section vs clock time. The area under this curve represents the total travel time of all vehicles in the section for the time period under consideration (7). Curves were plotted for two expressway sections (the control section and the upstream section) from the five best operational peak periods in each study phase.

The East-to-5th control section (Fig. 6) clearly shows direct control benefit between 4:35 and 6:20 p.m.; the area between the two curves represents a reduction in total travel time of 186 vehicle-hours. As noted previously in the congestion contour map (Fig. 5), control benefits are not realized until after 4:50 p.m. in the Kostner-to-East upstream section (Fig. 7). By the prevention of backups from the Des Plaines bottleneck between 4:50 and 6:10 p.m., however, an additional 110 vehicle-hours are saved.

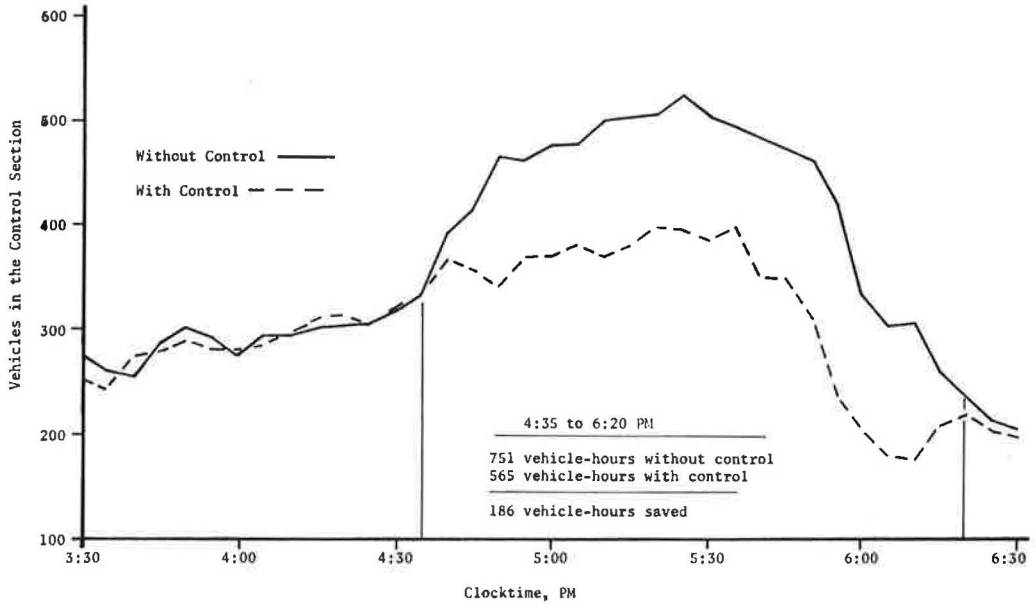


Figure 6. Number of vehicles in the control section (East to 5th).

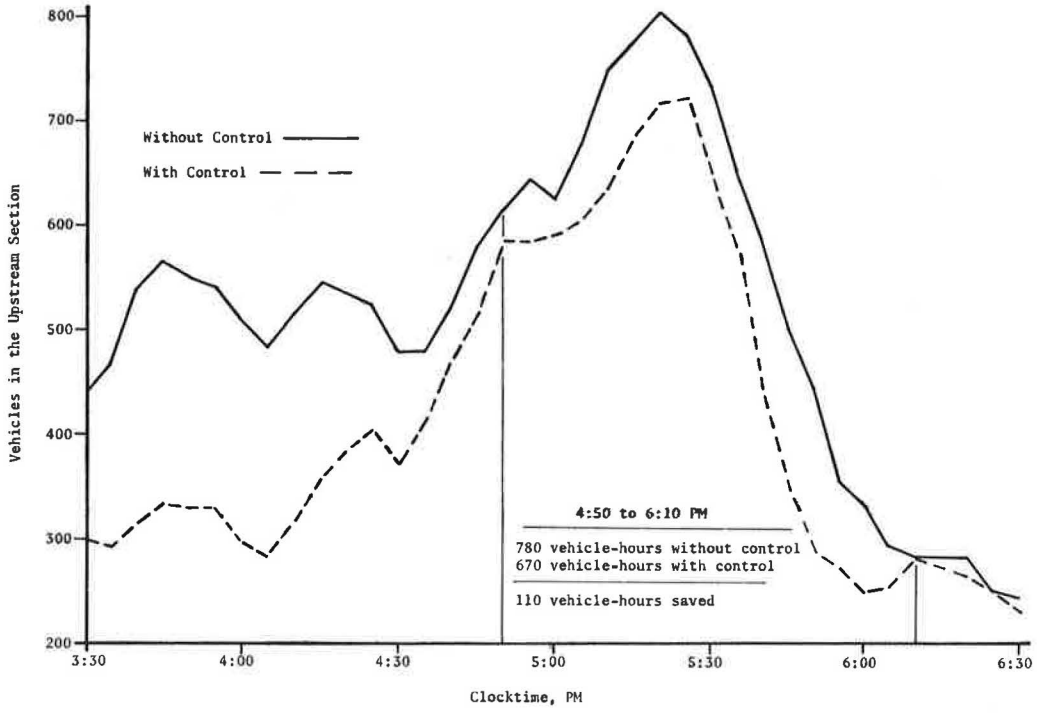


Figure 7. Number of vehicles in the upstream section (Kostner to East).

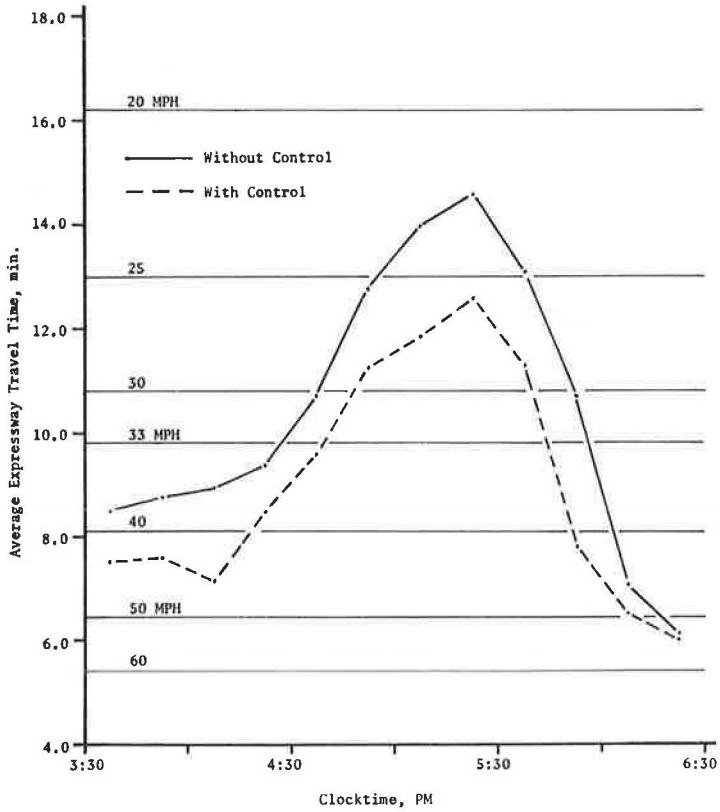


Figure 8. Individual trip travel times, Kostner to 5th (5.40 miles).

The total travel time changes prior to 4:50 p.m. in the upstream Kostner-to-East section cannot be attributed to the ramp control system unless expressway travel patterns were altered by control, an unlikely occurrence. Normal spring-to-summer, peak-period traffic demand decreases apparently produced most of these travel time changes. Slight demand reductions at the Austin lane reduction bottleneck seem ample to delay the introduction of peak-period congestion there in the summer months.

During the effective control period (4:35 to 6:20 p.m.), the total travel time savings due to ramp controls represent actual reductions in individual trip travel times, since the vehicle-miles of expressway travel were maintained or slightly increased. The direct control section benefits (186 vehicle-hours) combined with the incremental upstream Austin bottleneck section benefits (110 vehicle-hours) produce total ramp control benefits amounting to 296 vehicle-hours of reduced total travel time for expressway users between Kostner and 5th Avenues (5.40 miles).

Individual Travel Times

Since total travel time reductions are not evenly distributed among all expressway users, plots of actual trip travel times vs clock time provide estimates of control benefits experienced by individual motorists. Ramp controls produced trip travel time savings of up to 3 minutes for through (Kostner-to-5th) expressway users in the effective control period (Fig. 8), comparing the best operational peak periods with and without control.

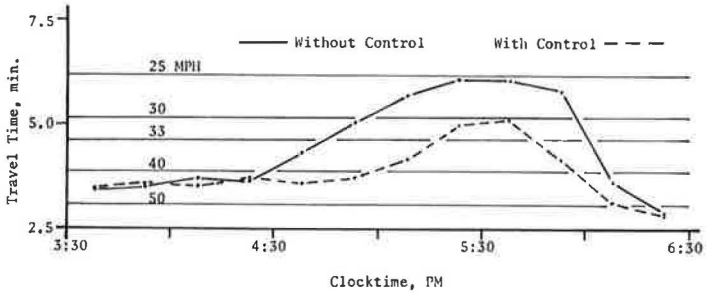


Figure 9. Control section trip travel times, East to 5th (2.59 miles).

The individual trip travel time graphs for the control section (Fig. 9) and the upstream section (Fig. 10) agree in general shape and overall magnitude with the total travel time graphs shown previously (Figs. 6 and 7), although the data collection and analysis techniques were basically independent. Favorable agreement with the congestion contour map (Fig. 5) is also possible by defining congestion on the trip travel time graphs as traffic operations at space mean speeds less than 33 mph, a quite reasonable definition.

Expressway Production

Regarding the effect of ramp controls on expressway traffic volumes, two areas of major interest are the actual expressway bottleneck section and the upstream expressway section. The upstream station at East Avenue (Fig. 11) shows non-congested volumes with ramp controls and congested volumes (beginning at 4:50 p.m.) without controls. The demand entering the control section was essentially the same on the best operational days prior to 4:50 p.m.

The prevention of the congestion backup from the Des Plaines bottleneck produced an increased expressway flow of 315 vph at East Avenue between 4:50 and 5:50 p.m. The volume differences after 5:50 p.m. are meaningless from a production standpoint, since the mainline demand at East Avenue decreases (non-congested flows with control),

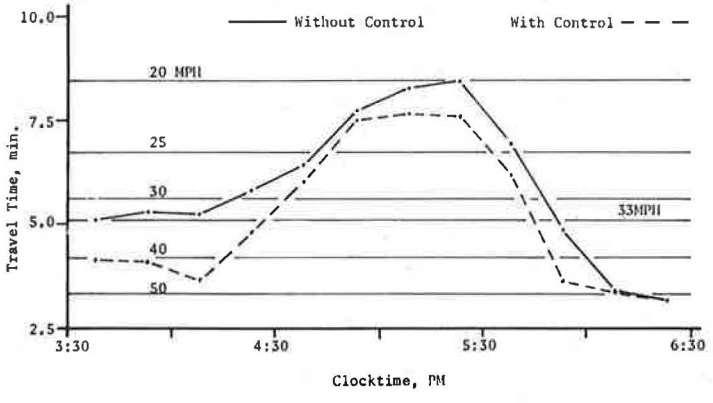


Figure 10. Upstream section trip travel times, Kostner to East (2.81 miles).

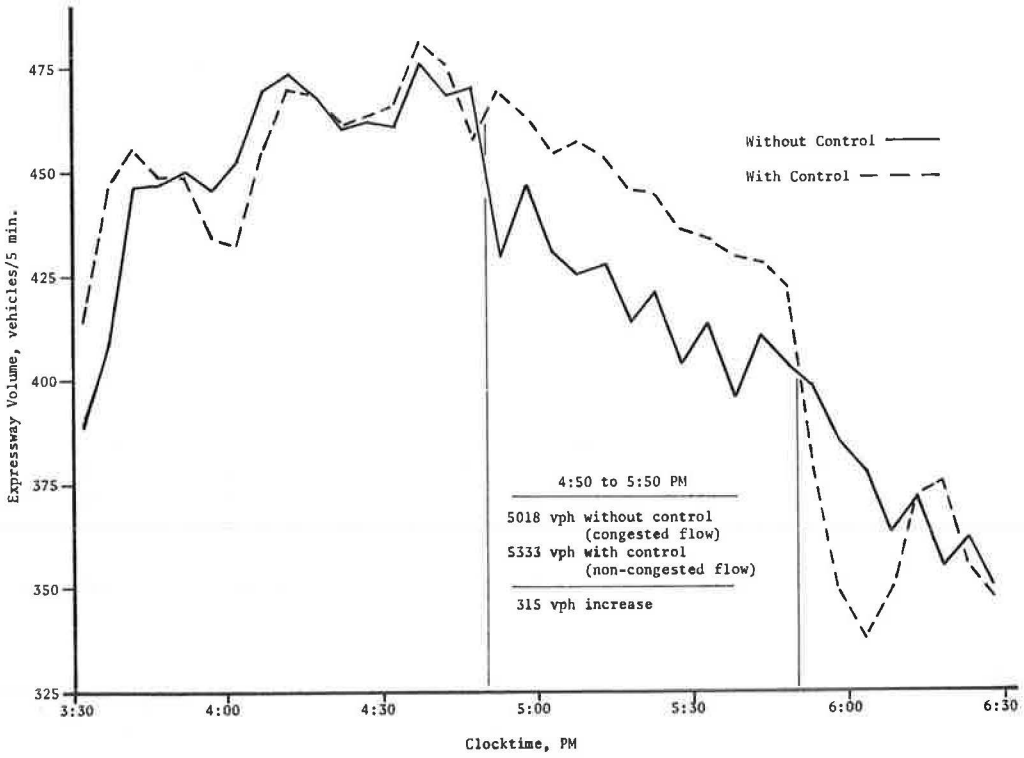


Figure 11. Expressway volume at East Avenue.

whereas the "before" volumes represent continued discharge from upstream congestion storage, a condition prevented by ramp controls.

The actual bottleneck output flow at the Des Plaines River (Fig. 12), meanwhile, decreased 49 vph in the critical control hour there (4:40 to 5:40 p.m.), indicating that upstream ramp controls do not necessarily increase long-term bottleneck outputs. The ramp controls, however, may have been slightly conservative from a bottleneck capacity standpoint.

A flow map for the critical control hour in the East-to-5th section (Fig. 13) shows the overall production effects produced by entrance ramp metering at Harlem and Des Plaines. Diversion of 325 vehicles between 4:45 and 5:45 p.m. at these ramps reduced expressway density and increased upstream flows without greatly changing the flow through the bottleneck and downstream. (Flow maps of this type require inclusion of density changes.) Under reduced expressway density conditions, the 325 diverted ramp vehicles were essentially replaced by 265 expressway vehicles (formerly stored on the congested upstream expressway) in the use of the expressway bottleneck in the ciritical control hour. Perhaps improved ramp control schemes will allow one expressway vehicle to replace each diverted ramp vehicle in passage through the Des Plaines bottleneck. It should be noted that the total outbound corridor output was increased, as diverted vehicles were absorbed on alternate routes.

The upstream flow increases generated through ramp controls were reflected through the Austin lane reduction bottleneck to the upstream study section limits at Kostner Avenue (Fig. 14). This graph also shows the slight demand decreases responsible for the delay in the introduction of congestion at Austin Avenue.

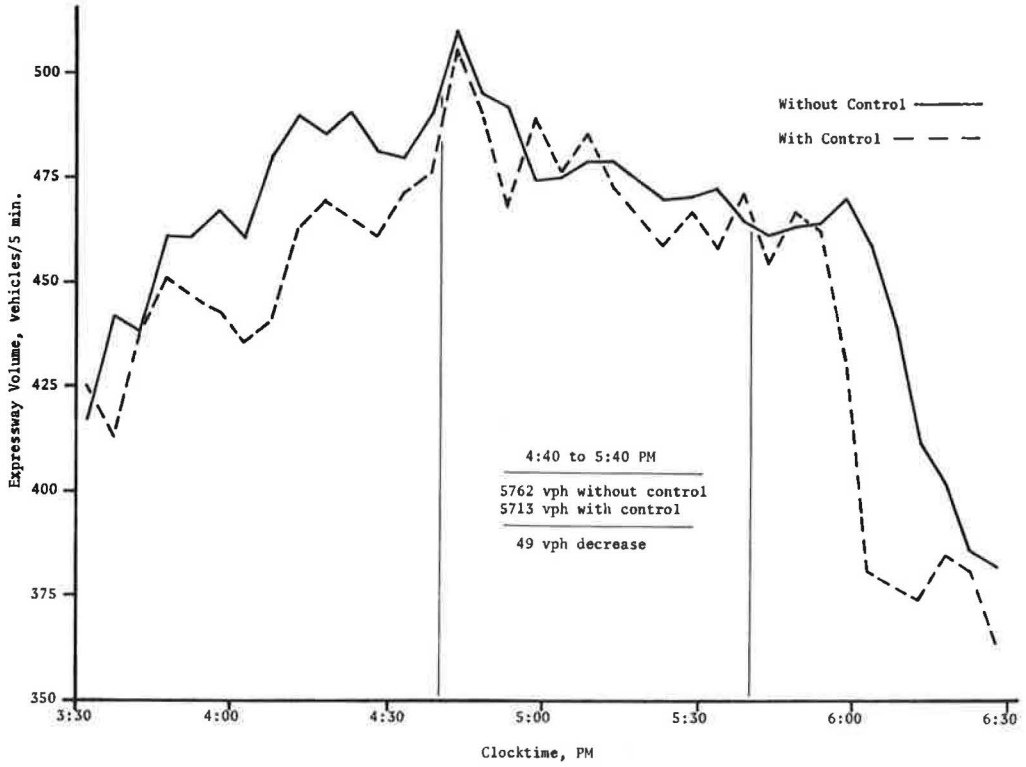


Figure 12. Expressway volume at Des Plaines River.

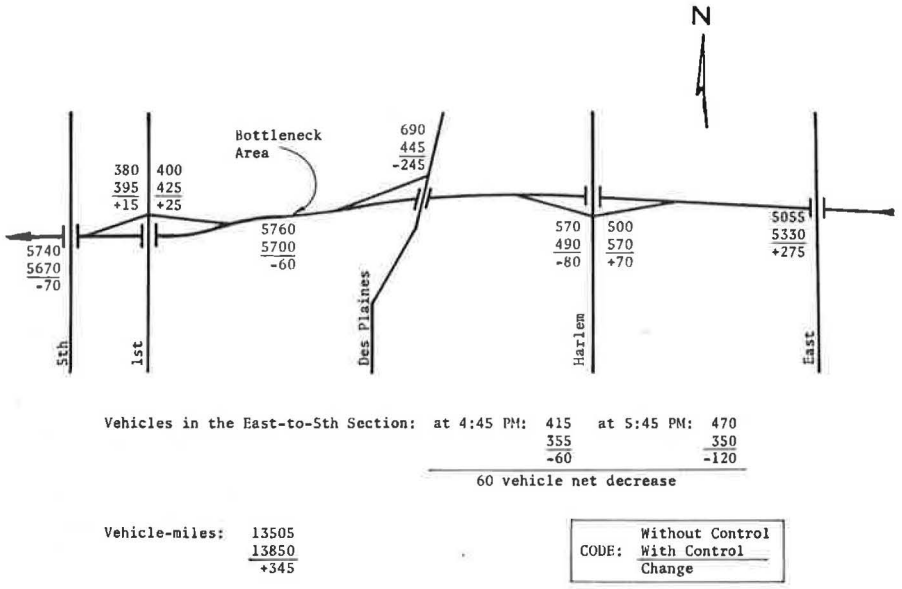


Figure 13. Expressway and ramp flow map, East to 5th, critical control hour (4:45 to 5:45 p.m.).

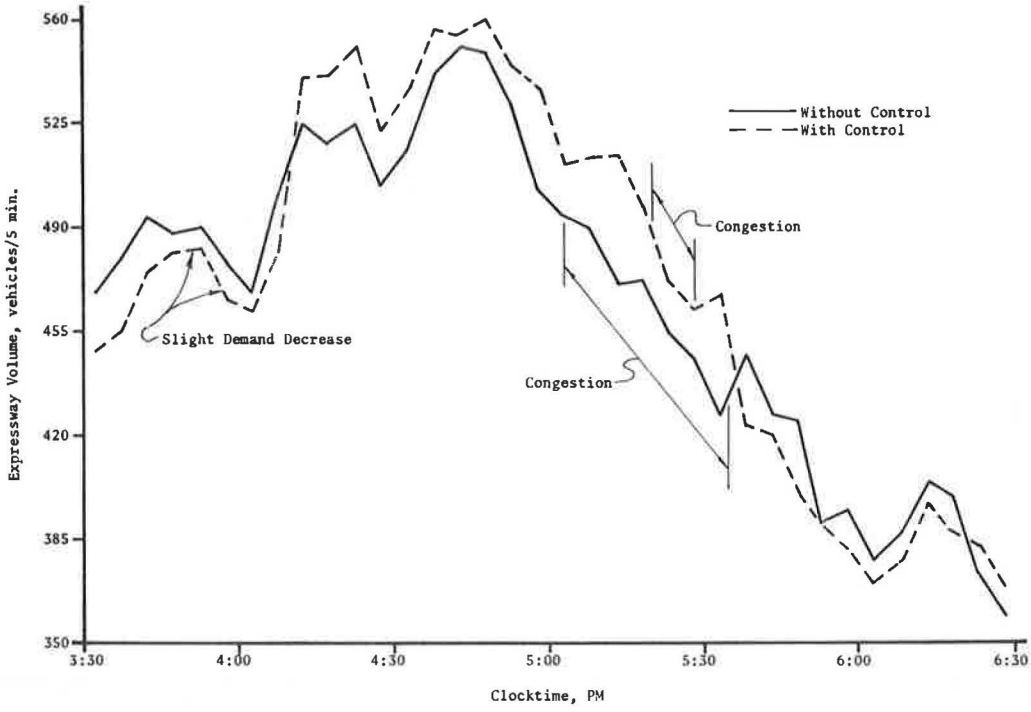


Figure 14. Expressway volume at Kostner Avenue.

Daily Performance Variations

It should be emphasized that the expressway findings presented thus far were derived by comparing only the best peak periods with and without ramp controls. Detailed analyses for all study days, however, demonstrated that the expressway does not operate at the same level each peak period. Even apparently comparable peak periods, free of obvious incidents and traffic disturbances, produced substantially different performance data, apparently due to subtle minor events, occurring within or outside the study section, which also complicate the basic expressway overloading problem.

The 1962 stopped vehicle study, for instance, pointed out that an overall average of one vehicle was stopped on the pavement or shoulders each hour per directional mile for some reason other than traffic congestion (9). Applying this overall factor to the 5.40-mile study section (even though the peak-period factor is somewhat higher), an average of more than 30 stopped vehicles in both directions could disturb traffic flow each outbound peak period (3:30 to 6:30 p.m.). Additional stoppages upstream or downstream of the study section could also cause backups and/or reduce flows within the data collection section.

It is not surprising, therefore, that the daily overall peak-period performance data exhibit a rather erratic pattern (Tables 1 and 2). The calculated vehicle-miles and vehicle-hours produce an overall "speed" parameter (vehicle-miles/vehicle-hours), which serves as a very useful indication of the operational level for each peak period. Ranking each peak period in descending operational levels (Figs. 15 and 16) shows that there were about ten peak periods with ramp control which were operationally better than the best peak period without control. The poorest peak periods are affected by the randomness of special expressway events (accidents, disabled vehicles, rain, etc.)

TABLE 1

OVERALL EXPRESSWAY PERFORMANCE WITHOUT CONTROL
(3:30 to 6:30 p.m.)

Date	Day	Kostner to Fifth (5.40 mi)			East to Fifth (2.59 mi)		
		Veh-Miles	Veh-Hours	"Speed"	Veh-Miles	Veh-Hours	"Speed"
4-27	Tu	—	—	—	40661	1117	36.4
4-28	W	—	—	—	38855	1150	33.8
4-30	F	75449	4403	17.1	35949	1157	31.1
5-3	M	78994	3804	20.8	37111	1446	25.7
5-4	Tu	84453	3243	26.1	39372	1034	38.1
5-5	W	83702	2788	30.0	—	—	—
5-6	Th	84406	2798	30.1	39663	1150	34.4
5-10	M	82834	3292	25.2	39269	1165	33.7
5-11	Tu	84321	2983	28.3	39822	1198	33.2
5-12	W	84392	2634	32.0	39580	1018	38.9
5-13	Th	75534	4185	18.1	35547	1656	21.5
5-14	F	82719	2660	31.1	39036	1234	31.6
5-17	M	86365	3636	23.7	40604	1324	30.7
5-20	Th	82761	2667	31.0	38732	1068	36.2
5-21	F	85596	2659	32.2	40093	1151	34.8
5-25	Tu	84579	2616	32.3	—	—	—
5-26	W	81693	2964	27.6	—	—	—
5-27	Th	82575	2672	30.9	—	—	—
6-4	F	85359	3140	27.2	40052	1335	30.0
6-7	M	86252	2845	30.3	40668	1152	35.3
6-9	W	84652	3311	25.6	39816	1188	33.5
6-10	Th	81732	3784	21.6	38579	1072	36.0
6-11	F	83706	3471	24.1	—	—	—
6-14	M	84735	2835	29.9	—	—	—
6-15	Tu	87191	2578	33.8	40984	1033	39.6
6-16	W	86843	2940	29.5	40609	1212	33.5

NOTE: Although attempts were made to analyze every commuting peak period in each study phase, unexpected detector malfunctions, computer problems, manpower shortages, and other limitations voided complete, accurate data collection for the peak periods omitted from Tables 1 and 2.

TABLE 2

OVERALL EXPRESSWAY PERFORMANCE WITH CONTROL
(3:30 to 6:30 p.m.)

Date	Day	Kostner to Fifth (5.40 mi)			East to Fifth (2.59 mi)		
		Veh-Miles	Veh-Hours	"Speed"	Veh-Miles	Veh-Hours	"Speed"
6-21	M	85632	2276	37.6	39696	1060	37.4
6-22	Tu	84772	2680	31.6	39257	1061	36.9
6-24	Th	85929	2707	31.7	40030	976	41.0
6-25	F	85919	2469	34.8	39985	1324	30.2
6-28	M	83823	2436	34.4	—	—	—
6-29	Tu	84597	2209	38.3	39356	940	41.8
6-30	W	83158	2725	30.5	—	—	—
7-1	Th	85612	2398	35.7	—	—	—
7-6	Tu	79315	3214	24.7	36137	1471	24.6
7-7	W	84951	2145	39.6	39215	830	47.2
7-8	Th	78555	1986	39.5	35872	944	38.0
7-9	F	84939	2295	37.0	39470	1011	39.0
7-12	M	—	—	—	39302	822	47.8
7-13	Tu	—	—	—	38821	831	46.7
7-14	W	86119	2574	33.4	40041	971	41.3
7-16	F	86304	2065	41.8	40030	1013	39.6
7-19	M	—	—	—	39916	841	47.5
7-21	W	—	—	—	39487	1054	37.5
7-22	Th	83709	2242	37.3	38511	870	44.2
7-23	F	—	—	—	38972	1071	36.4
7-26	M	83118	2641	31.5	38491	1132	34.0
7-28	W	85545	2671	32.0	39687	1063	37.3
7-29	Th	85271	2370	35.9	39537	916	43.1
7-30	F	—	—	—	40546	994	40.8
8-3	Tu	66630	3562	18.7	30999	1293	24.0
8-4	W	79845	2807	28.4	36991	1162	31.8
8-5	Th	82696	2928	28.2	38568	1007	38.3
8-6	F	84870	2369	35.8	39356	1107	35.5

See footnote to Table 1.

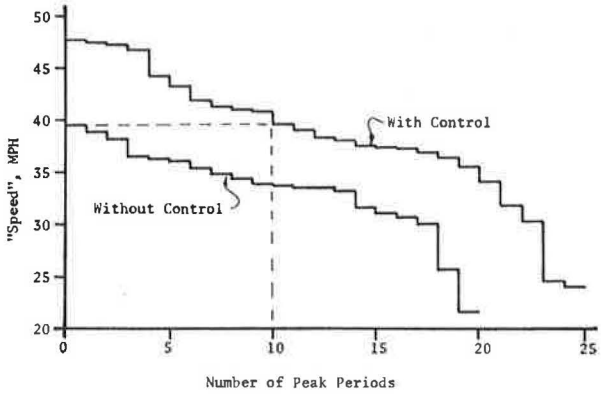


Figure 15. Ranked overall peak-period performance, East to 5th (2.59 miles).

occurring at the "wrong" time and place; the control benefits, if any, in these situations are difficult to measure because of radically dissimilar circumstances.

The long duration of the ramp control evaluation supplied a library of operational data heretofore not obtained for expressway traffic. The daily range of overall performance for "incident-free" peak periods points out the need for long study durations in order to avoid comparing "good" days with control and "fair" days without control, or vice versa (10).

Expressway Accidents

The ranked daily performance data establish that ramp controls allow the expressway to operate at levels higher than possible without controls. Expressway accident data, however, suggest that ramp controls actually cause "good" peak-periods on some occasions by preventing the occurrence of special events which inititate "poor" peak periods. Traffic accident data compiled by the Chicago Area Transportation Study (Fig. 17) indicate a 14.4 percent reduction (444 to 380) in outbound expressway (and

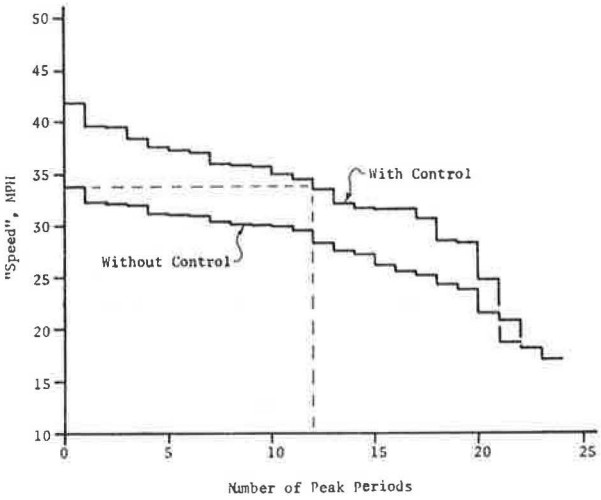


Figure 16. Ranked overall peak-period performance, Kostner to 5th (5.40 miles).

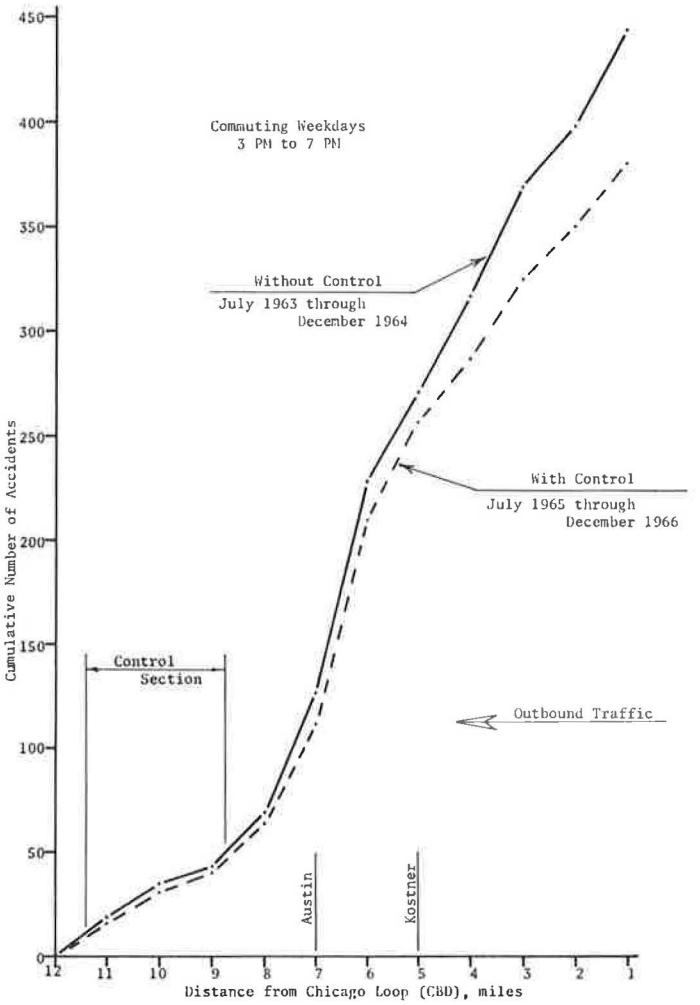


Figure 17. Peak-period accidents, westbound Eisenhower Expressway, commuting weekdays, 3:00 to 7:00 p.m.

ramp) peak-period accidents in the 18 months following commencement of the entrance ramp control system. All other Eisenhower Expressway accidents for the same length of roadway (including inbound peak-period accidents) increased 2.9 percent (2240 to 2306) during the same 18-month period. Assuming outbound peak-period accidents might have increased at this same rate without the ramp control system, the net prorated accident reduction amounts to 16.8 percent (457 to 380).

It is most probable that the reduced outbound peak-period traffic congestion accomplished through the ramp control system is responsible for the decrease in accidents recorded. The upstream propagation of ramp control benefits, such as more "good" peak periods, fewer congested sections, and shorter congestion periods, is reflected by accident reductions mainly in sections upstream of the control section. The favorable accident experience sustained through 18 months of ramp control offers statistically significant evidence of safer expressway traffic operations (11). Moreover, the favorable decrease in congestion and accidents suggests that other expressway operational benefits, such as the reduction of disabled vehicles and reduced air pollution, are also produced by effective ramp controls.

TABLE 3

DAILY ENTRANCE RAMP METERING STATISTICS
(Averages of 50 Control Periods)

Category		Harlem	Des Plaines	First	Seventeenth
Ramp traffic, vehicles		1272	1095	1036	1036
Signal violations, vehicles		49	32	26	30
Signal compliance rate, percent		96.1	97.1	97.5	97.1
Range	Low	93.9	94.8	92.7	93.4
	High	98.5	98.8	99.0	98.8
Control period, minutes		170	169	165	163
Ramp flow rate, veh/min		7.46	6.47	6.26	6.37

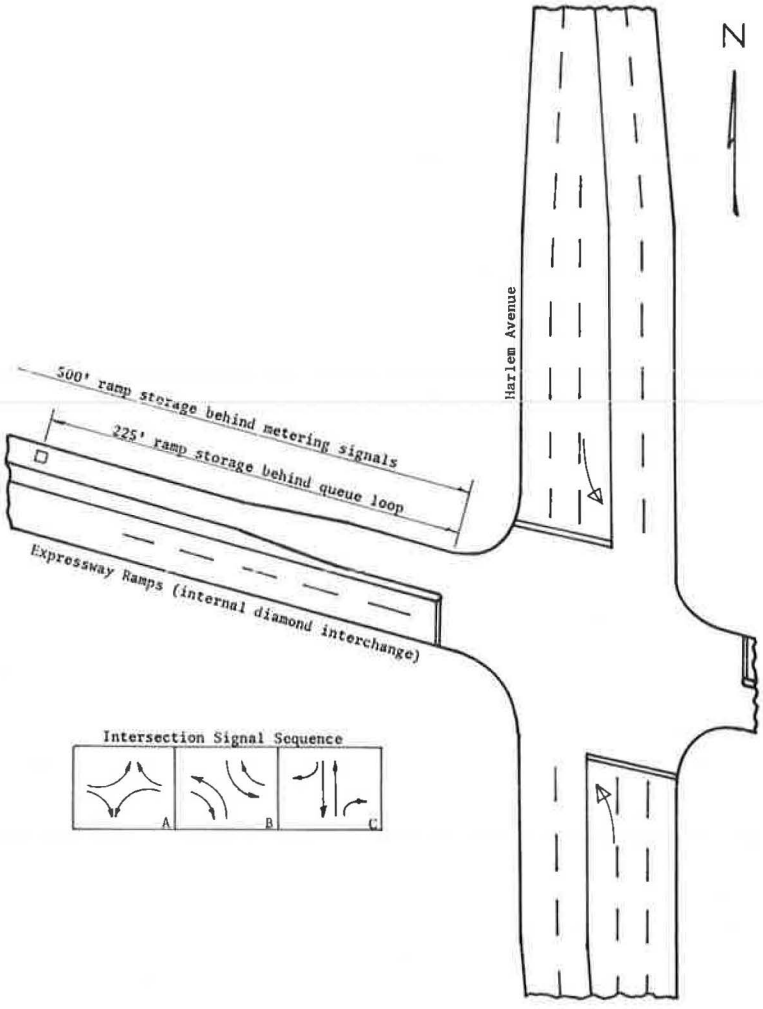


Figure 18. Harlem Avenue intersection with Eisenhower Expressway ramps.

ADVERSE CONTROL EFFECTS

Although ramp metering controls provide operational improvements in expressway traffic flow, ramp delays and surface street friction can result from ramp queues and diversion. Experience with the experimental control system has demonstrated that the major problem of peak ramp demands exceeding the general operational capacity range of each metering device is greatly lessened by gradual traffic adjustment to repetitive metering delays, after an introductory week or two of rather severe queuing problems. Thereafter, day-to-day variations in local metering patterns produce some ramp and surface street delays, especially when expressway traffic flow deteriorates.

Generally, there are no major ramp queuing and surface street problems resulting from ramp controls as long as expressway traffic operations remain non-congested. Inasmuch as the ramp metering rates automatically fluctuate up and down to accommodate the surges common to a high-volume, non-congested expressway traffic stream, a fairly predictable entrance ramp capacity and delay pattern becomes established. The existence of expressway congestion, however, produces sustained restrictive ramp metering, which in turn develops ramp queues extending back into the surface street network. Thus, the least interference with ramp and surface street traffic occurs during the best expressway peak periods, due mainly to the characteristics of the ramp control logic.

Ramp Operations

The effect of each metering device on entrance ramp traffic behavior is similar to findings reported previously for the initial First Avenue installation (3). Motorist acceptance of the "one-at-a-time" metering scheme is reflected by an average red signal compliance rate of over 96 percent at all four sites (Table 3). The queuing and diversion patterns differ for each ramp, however, due to the variation in geometric and traffic characteristics affecting the attractiveness of parallel alternate routes.

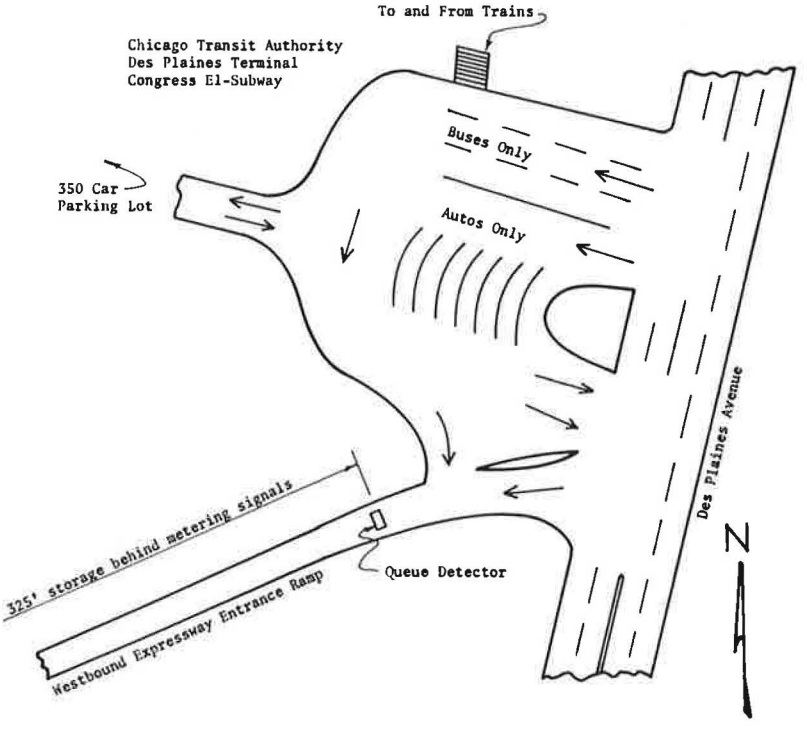


Figure 19. Des Plaines Avenue intersection with westbound Eisenhower Expressway entrance ramp.

The adverse effects of ramp controls at First Avenue and 17th Avenue are insignificant, inasmuch as the expressway flow through this corridor is usually non-congested, a condition producing no severe ramp queuing problems. At the critical Harlem Avenue and Des Plaines Avenue entrance ramps, however, stringent metering periods are usually required each day after congestion develops in the Harlem-Des Plaines expressway area. The lack of frontage roads or other convenient alternate routes at these sites forces ramp queuing, permanent diversion, and daily (optional) diversion.

The Harlem interchange geometrics (Fig. 18) and ramp demand approach patterns confine adverse effects to queue delays and diversion delays, if any. Queuing interference with surface street traffic is minimized by the ample storage areas on the ramp and in the right-turn bay. Left turns onto the metered ramp are favored by the intersection signal sequence, but the low traffic demand from this direction makes it practical to store left-turn vehicles on the ramp each signal cycle, thereby avoiding intersection friction by left-turn queue blockages.

The Des Plaines interchange geometrics (Fig. 19) are complicated by the presence of the rail-rapid-transit terminal parking lot at the entrance ramp head. Severely peaking traffic movements, generally following train arrivals, produce considerable intersection friction attributable to ramp queuing. In most cases, ramp delays are not overly severe, but queue blockages of turning movements into and out of the various driveways impose delays on non-expressway-bound traffic.

Ramp Delays

On good expressway operational days, all metered ramp demands are handled with little trouble; ramp queues are confined to the ramps or immediate approach storage areas. On poor operational days, queue lengths seldom exceed 30 vehicles, due to diversion from long and/or slow queues. Ramp delays, then, are minimized under non-congested expressway flow conditions.

Inasmuch as ramp delays for the 250 to 350 feet of storage area immediately behind each metering device were automatically included in the total expressway travel time computation by using queue detector volumes for the metered ramp inputs, the remaining ramp delays are estimated for periods of queuing beyond the ramp queue detector. On the better expressway operational days, only the Harlem and Des Plaines entrance ramp delays are significant enough to measure:

	Harlem	Des Plaines
Queuing Period	4:00 to 5:35 p.m.	4:35 to 5:40 p.m.
Total Time Queued	65 minutes	45 minutes
Estimated Delay	10 veh-hr	10 veh-hr

Although ramp queues extending beyond the queue detector occur more often at Harlem than at Des Plaines, the more severe Des Plaines queuing produces the same total delay as Harlem, 10 vehicle-hours.

Surface Streets

Besides imposing delays on motorists enduring ramp queues, ramp metering controls produce permanent and optional diversion to alternate routes. Diverted ramp traffic may not only experience increased travel times and/or trip lengths, but also may contribute to existing surface street congestion at critical intersections (2). Comprehensive studies of the surface street network, however, have failed to uncover any deterioration of surface street traffic operations attributable to the ramp controls except at the entrance ramp-arterial street terminals where queues interfered with traffic movements.

Because expressway traffic congestion compounds ramp queuing, the least surface street interference is caused during the best expressway peak periods. The following minimum diversion magnitudes (3:30 to 6:30 p.m.) for the critical Harlem and Des

Plaines ramps consist of permanent diversion and optional diversion, the latter being generated by inspection of ramp queues and/or utilization of the informational display signs, details of which are covered in another report (5).

	Harlem	Des Plaines
Total Diversion	123	384
Optional Diversion	109	68
Permanent Diversion	14	316

Optional diversion varies each peak period with expressway traffic conditions; repetitive delays eventually cause some optional diverters to select permanent alternate routes. The gradual increase of permanent diversion results from restrictive metering control on poor expressway days. Although the metering pattern eventually stabilizes the metered ramp demand, permanent diversion produces vacant ramps (especially at Des Plaines) for some periods on good expressway days. Thus, even though motorists comply with the ramp signals, widely varying controls do not appear to be tolerable. This characteristic, however, is more a reflection of the inaccessibility and inconvenience of alternate routes than an indication of control inflexibility. The permanent diversion component is practically nonexistent where continuous one-way frontage roads parallel the expressway (3).

It does not appear that ramp diversion greatly affects either surface street traffic or diverted traffic except at the complicated Des Plaines entrance ramp terminal. Diversion magnitudes at Harlem (Fig. 20) and Des Plaines (Fig. 21) are distributed over much of the peak period, such that diverted traffic is unlikely to be overloading any specific surface street links. The variations in trip origins and destinations also cause several alternate routes to absorb the diverted traffic (12).

It is suspected that many diverted expressway trips are short in length, particularly at the Des Plaines ramp, where the previous convenience of expressway ramp access

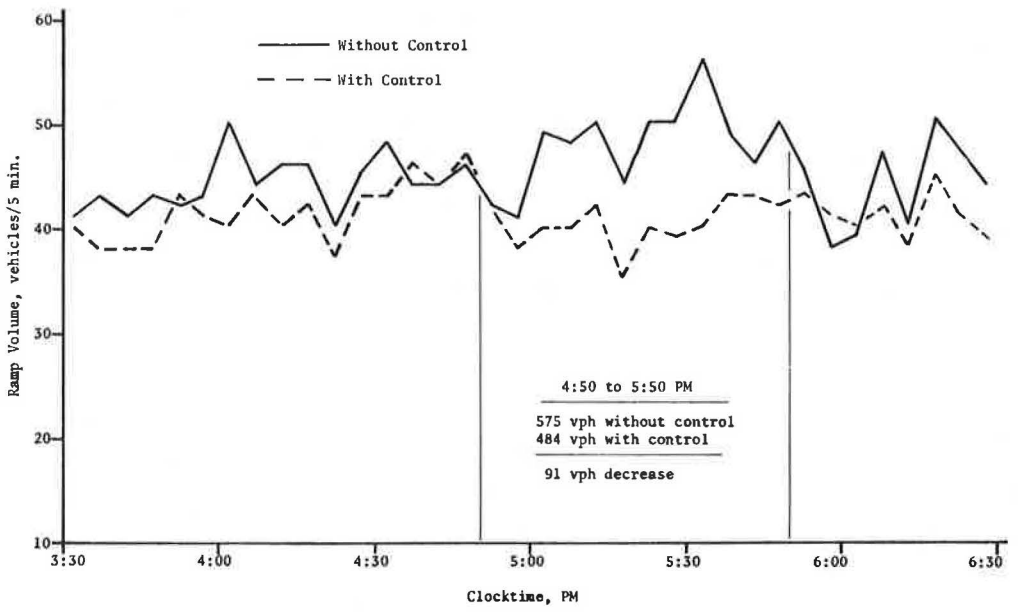


Figure 20. Harlem Avenue entrance ramp volume.

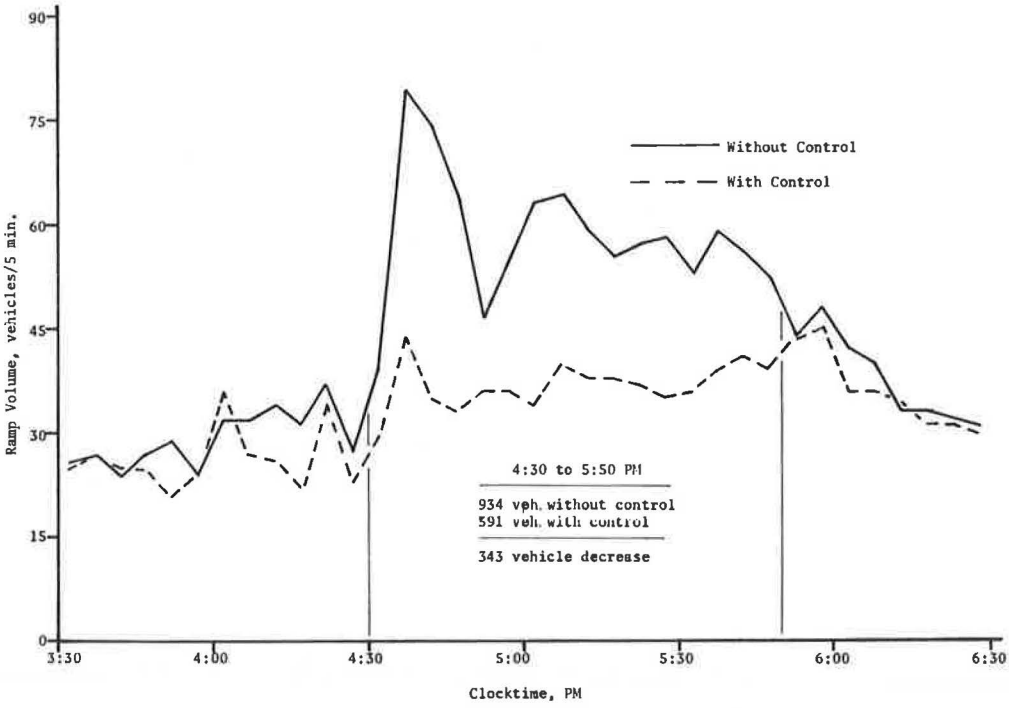


Figure 21. Des Plaines Avenue entrance ramp volume.

attracted "park-and-ride" rail transit patrons not necessarily inconvenienced by alternate surface street routes (12). Nevertheless, although many permanent diverters experience no increased travel time, it seems reasonable to assign a 2-minute increased travel time to all diverted vehicles for the purposes of delay computation, thereby consuming 20 vehicle-hours of total extra surface street travel time.

The major surface street problem is reflected by the response of the affected motorists. Fewer than ten complaints have been received from motorists annoyed at the ramp controls. Most of these complaints concerned delays at Des Plaines, not so much in ramp queues, but in the chaos of turning movements blocked by ramp queues and affecting both expressway and non-expressway users. This particular problem has been alleviated by the installation of conventional traffic signals at the ramp entrance-transit parking lot-Des Plaines Avenue intersection. Future research will coordinate signal timing with ramp queuing; emphasis will be placed on the reasonable allotment of entrance ramp right-of-way while minimizing interference with non-expressway-bound traffic.

CONTROL REFINEMENTS

Research with metering controls at four successive entrance ramps has reduced expressway traffic congestion caused by overloading the Harlem-Des Plaines section of the outbound Eisenhower Expressway. However, the combination of uncontrolled mainline flows and sensitive section geometrics prevents the elimination of peak-period congestion or recovery to non-congested operations once congestion has been introduced under peak flows.

Inasmuch as the advent of traffic congestion during peak expressway flows minimizes the obvious operational improvements produced by ramp metering, the adverse effects transmitted to the contiguous surface street network by stringent ramp controls can be reduced or eliminated by adjustments in the ramp control schemes. In order to prevent

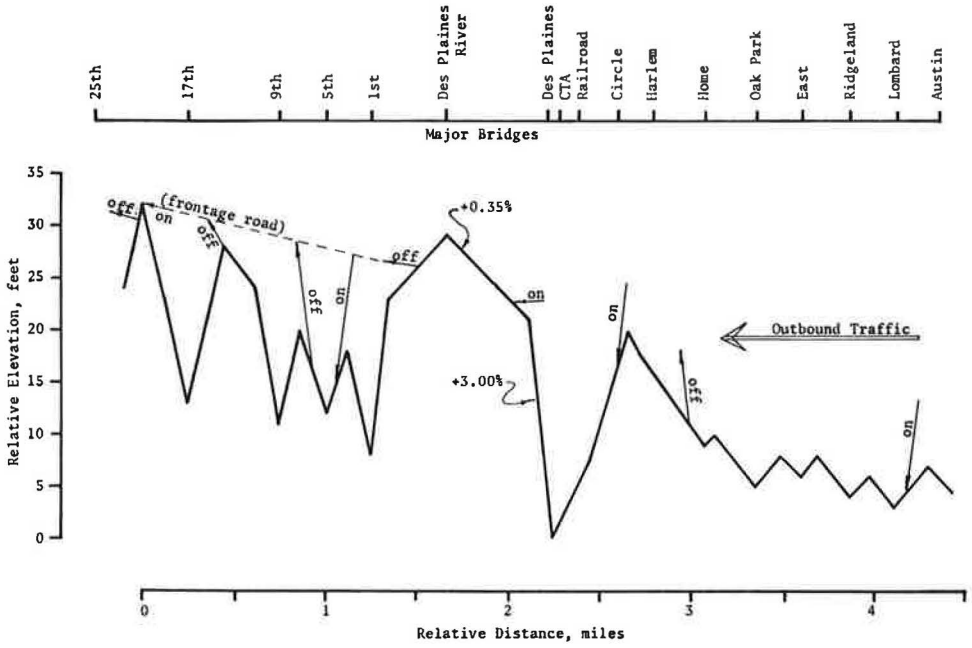


Figure 22. Westbound Eisenhower Expressway profile.

the introduction of expressway traffic congestion, however, more control of the expressway demand reaching critical capacity sections is needed. Thus, control refinements have been developed to provide an operational mode (rather than a research mode) for the present control system and to furnish an expanded control system providing upstream mainline demand reductions.

Operational Adjustments

The major operational problem in the present control section is now the sensitive Des Plaines upgrade (Fig. 22). As suspected, two bottlenecks had existed, the Des Plaines entrance ramp merging area and the critical upgrade. Elimination of severe entrance ramp surges and expressway overloading in the merging area has made the upgrade area the controlling capacity section (especially since the ramp controls increase flows on the upgrade such that the upgrade capacity is eventually exceeded). Once congestion develops in the upgrade area under peak traffic demands, the restoration of non-congested operations has not been possible due to the inability of restrictive metering at the only upstream metered ramp (Harlem) in overcoming the upgrade characteristic of maintaining congestion until the mainline demand decreases significantly at the end of each peak period.

Hence, whenever congestion exists on the Des Plaines upgrade after 4:40 p.m., regardless of the cause, non-congested flow cannot be restored by the present ramp control system (unless an unusual upstream event temporarily reduces the mainline flow reaching the upgrade bottleneck). Restrictive ramp metering, therefore, is now utilized only when congestion does not exist or when recovery from congested traffic operations appears possible (prior to 4:40 p.m. when congested flow rates can be greater than sustained mainline demand rates). In all other peak-period congestion situations, including accidents and other events that increase expressway density beyond the practical influence of the ramp controls, upstream ramps are metered to satisfy actual ramp demands, thereby avoiding most ramp and surface street problems.

Metering Schemes

Several control schemes for operating individual ramp metering devices and systems composed of two or more consecutive metered entrance ramps have been proposed, formulated and tested (1, 2, 3, 4, 13, 14). All schemes decrease allowable entrance ramp inputs upon detected evidence of increased impending expressway traffic congestion. The object of most control schemes is the maximization of expressway-ramp merging volumes and/or critical bottleneck outputs without causing congested traffic operations. Inasmuch as the present degree of control has not sufficiently reduced the expressway mainline demand below the geometric capacity of the critical Des Plaines upgrade, the resulting daily upgrade congestion makes it difficult to measure operational differences between most alternate control schemes, especially since limitless technique refinements are within the range of day-to-day operational variations.

Uncontrollable daily variables, such as prevailing weather conditions and visibility restraints (sun glare, winter darkness, etc.) can impose a lower than ideal operating capacity on the Des Plaines upgrade. Operational traffic factors, such as seasonal and daily demand variations and the prevailing distribution of commercial vehicles, produce additional effects in the control section. (Trucks are restricted to the two right expressway lanes; the left-hand Harlem entrance ramp forces truck lane-changes on or immediately preceding the critical Des Plaines upgrade.) The most significant operator on the critical Des Plaines upgrade, however, is the uncontrolled output of the upstream Austin lane reduction bottleneck, which supplies most of the traffic demand entering the present control section. All these factors produce daily variations in the interaction between traffic flow and physical geometrics which permit the present control section to be operated according to numerous metering schemes without producing measurable evidence of the most effective technique.

Alternate automatic control schemes presently used include local metering control based on expressway lane occupancy measurements upstream and/or downstream of the merge area and system control based on upstream non-congested expressway volumes and occupancy levels throughout the control section (4). Analog computer methods are usually employed for local control schemes; a small, real-time, digital control computer provides the flexibility needed for the more sophisticated system control techniques. Whether the automatic metering schemes are under analog or digitial control, manual override capabilities allow selection of any desired metering rate at any or all metered ramps. In normal (non-research) day-to-day operations, one of the automatic control modes is employed until non-recovery type congestion occurs; manual override control is utilized thereafter at ramps feeding congested expressway sections to prevent ramp queues from seriously disturbing surface street traffic operations.

Although the present ramp control system has been unable to prevent eventual daily peak-period expressway overloading congestion, the introduction of congestion has been effectively delayed. However, any Des Plaines upgrade disturbances in peak flows can easily trigger shock waves to change traffic operations from a "super-sensitive," non-congested state to the inevitable congested state. Thus, both macroscopic and microscopic control parameters must predict or reflect traffic conditions on the brink of breakdown, so that entrance ramp merging turbulence can be minimized by restrictive metering.

All but one of the tested metering schemes have been reasonably effective in responding to critical conditions of impending congestion (even though enough physical control is not available at all times to prevent congestion). Inasmuch as traffic entering the expressway stream at right-hand entrance ramps must initially merge with the shoulder lane, traffic measurements in the shoulder lane preceding the merge area seem intuitively obvious as one-lane control parameters. Metering attempts based on shoulder lane measurements, however, have been relatively ineffective in responding to mainline traffic surges (possibly due to the Chicago area lane-use restrictions which confine trucks to the two right lanes). It has been observed that initial overloading shock waves tend to occur on Chicago area expressways from left to right, even though merging ramp traffic initially enters the shoulder lane. It is suspected that downstream

lane changes by entrance ramp traffic into the high-volume, high-speed left lanes initiates overloading congestion; the unstable volume fluctuations in the low-volume shoulder lane do not reflect these impending problems.

System Extension Upstream

Entrance ramp metering systems apply to expressway situations where mainline demand exceeds capacity. Expressway capacity, however, depends not only on the physical geometrics along the traveled way, but also on the uncontrollable variables (percent trucks, weather, etc.) encountered in day-to-day traffic operations. Hence, in order to prevent expressway overloading congestion, enough control flexibility must be provided to insure that demand flow rates remain lower than prevailing capacity flow rates throughout the control system. Moreover, should congestion develop despite ramp controls, sustained demand flow rates lower than actual congested flow rates must be provided to restore non-congested traffic operations. Inasmuch as non-congested operating volumes can approach prevailing capacity levels, whereas congested expressway sections necessarily exhibit reduced operating volumes, it is not only more desirable to prevent overloading congestion than to recover from congested operations, but also easier to accomplish (less restrictive ramp controls). It follows, therefore, that locations regularly encountering overloading congestion despite ramp controls will not likely experience recovery from congestion via the same ramp controls.

In the case of the Des Plaines upgrade, by delaying or diverting expressway-bound traffic, Harlem and Des Plaines entrance ramp controls increased non-congested upgrade flows to the extent that upgrade capacity was regularly exceeded. Although the sensitivity and capacity characteristics of the upgrade had not been fully realized prior to the ramp control study (due to the previous overwhelming merging problem), it is now obvious that more upstream ramp controls are needed to prevent over-capacity

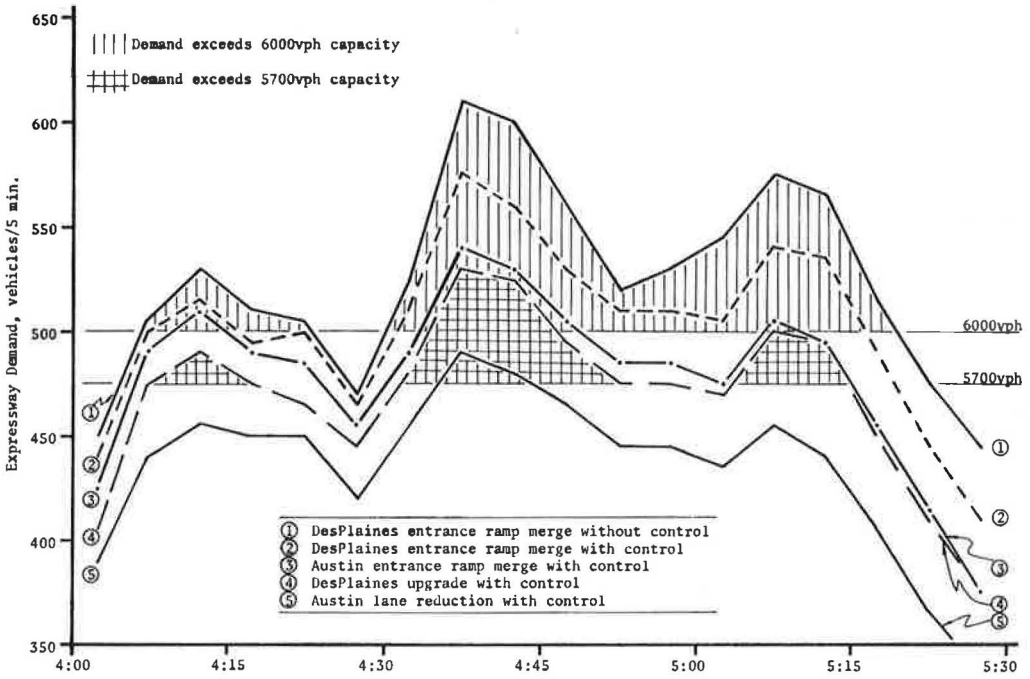


Figure 23. Expressway demand at critical locations.

mainline flows from reaching the critical upgrade. Even subtle mainline surges (independent of ramp merging friction) can develop upgrade shock waves which can propagate upstream to produce sustained peak-period congestion.

The theoretical demand for several expressway sections under the present control system (Fig. 23) was estimated by projecting non-congested upstream flows (at Kostner Avenue) downstream with adjustments for each entrance and exit ramp. The effect of present ramp controls (Harlem and Des Plaines) on the demand at the Des Plaines entrance ramp merge is also presented. The maximum sustained capacity for three-lane expressway sections is 6000 vph, except at the Des Plaines upgrade and Austin lane reduction bottlenecks, where geometric limitations impose a maximum sustained capacity of about 5700 vph. Again, the sustained level of service can be lower on days when uncontrollable variables override the ideal geometric capacity.

Three distinct, critical demand surges occur in each peak period, each surge following each half-hour beginning at 4:00 p.m. Generally, operational problems develop at the first outbound friction point where demand exceeds capacity; the flow downstream and on congested upstream sections is then reduced, as demand for downstream locations becomes delayed temporarily by storing on the expressway. Once congestion has developed, storage queues on the expressway increase until the demand no longer exceeds the congested flow rate.

The 4:00 to 4:30 p.m. demand surge presents potential problems at the Austin entrance ramp merge, the Des Plaines upgrade and the Des Plaines entrance ramp merge. The slight overloading, however, actually occurs initially at the Austin entrance ramp merge, the overloading increment having been introduced by Austin entrance ramp traffic. Although seemingly minor in degree, this merging turbulence is sufficient to trigger premature sustained congestion at the upstream Austin lane reduction bottleneck, illustrating the tendency of most major bottlenecks to bog down when subtle downstream events introduce congestion, thereby masking the real causes. It is expected that ramp metering at Austin Avenue would often prevent this minor overloading. Slight summer demand reductions were ample to delay Austin congestion during the control study.

If the 4:00 to 4:30 p.m. flow rate through the Austin entrance ramp merge is high enough, overloading can occur on the Des Plaines upgrade or at the Des Plaines entrance ramp merge. Usually the present control system can either prevent this problem or aid recovery of non-congested flow, inasmuch as the expressway demand drop prior to 4:30 p.m. is sufficient to dissipate mild congestion.

The major demand surge between 4:30 and 5:00 p.m. places all expressway sections (Fig. 23) potentially over capacity, but the two major bottlenecks at Austin and Des Plaines control the actual flow rates. Sometimes the present control system prevents upgrade congestion through this second surge (under poor Austin bottleneck operations), but the third mainline demand surge between 5:00 and 5:30 p.m. has been heretofore insurmountable.

In terms of theoretical demand exceeding maximum sustained capacity, the expressway section in the Des Plaines entrance ramp merging vicinity presents the greatest overloading potential. Although the present Harlem and Des Plaines entrance ramp controls have cut mainline demands somewhat, additional controls are needed upstream to further reduce mainline demands, such that, with enough control, no prevailing expressway capacity levels will be exceeded. Thus, by preventing overloading congestion in the present control section, an extended control system should also prevent congestion at the Austin lane reduction bottleneck, thereby eliminating the two major expressway bottlenecks during many outbound commuter peak periods.

SUMMARY OF FINDINGS

The experimental expressway traffic control system demonstrates that automatic entrance ramp metering can be a practical remedy for congestion caused by expressway overloading. Excellent motorist compliance with the one-vehicle-at-a-time scheme of the metering traffic signals permits a significant reduction in expressway congestion by delaying and diverting entrance ramp traffic. Although some geometric restraints

and uncontrollable variables are insurmountable with the present control system, significantly higher and safer overall expressway operational levels are provided than without control.

A net overall control savings of 256 vehicle-hours of total travel time (296 vehicle-hours saved by expressway users; 40 vehicle-hours additional delay to metered and diverted ramp traffic) was produced on the expressway, ramps and contiguous surface streets, comparing the best peak periods with and without control. Ramp controls substantially increased upstream expressway flows, without greatly changing downstream bottleneck outputs. Adverse metering effects attributable to ramp queuing and diversion were noticeable only at the metered ramp heads; restrictive metering controls tended to promote permanent diversion to alternate routes.

Inasmuch as the greatest control benefits are probably realized when non-congested expressway flows are maintained, the feasibility of extending the present control system to include enough upstream metered ramps to allow the further reduction of overloading congestion should be thoroughly investigated. Although careful and seemingly superfluous evaluation has demonstrated the value of ramp control systems to urban peak-period expressway operations, further detailed research is needed prior to all practical applications to insure that the degree of ramp control required does not produce adverse traffic effects negating the derived expressway benefits.

ACKNOWLEDGMENT

This paper also constitutes Report 17 of the Chicago Area Expressway Surveillance Project, sponsored by the Illinois Division of Highways in cooperation with the Bureau of Public Roads, Cook County, and the City of Chicago. The author wishes to express his gratitude to the Project staff, especially to Patrick J. Athol, Project Supervisor, for contributions to this report.

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Discussion

DONALD F. PETTY, Engineer of Traffic Research, Indiana State Highway Commission—The findings presented in this report are well documented and are another large step toward justifying the use of freeway traffic controls on an operational basis. My limited experience in the field of traffic surveillance and control has been related to the National Proving Ground for Freeway Surveillance Control and Electronic Traffic Aids in Detroit. This discussion covers my reactions to the investigation as viewed from experience on the John C. Lodge Project. The National Proving Ground has used considerably different equipment and techniques for accomplishing similar purposes as the Chicago Area Expressway Surveillance Project. However, one area of the project parallels this study to a great extent—the study on the effect on freeway traffic from closing on-ramps. Although the technique is different, it attempts to reduce congestion on the freeway and also diverts traffic to surface streets. The following conclusions resulted from two studies, and each supports or reinforces the findings made in this study:

1. General increases in volumes of traffic and decreases of travel time were found to result from the closing of on-ramps. More specifically, it was found that volumes were increased as much as 13.7 percent.
2. Lane stoppages were reduced as much as 92.5 percent.
3. It was found that non-congested traffic flow can be restored much faster with ramp control. One incident was reported in which a stalled vehicle affected three lanes of traffic. By closing two ramps, the congested traffic was cleared and all traffic was moving in 22 minutes. Normally, this would have required over one hour when relying on natural processes.
4. In each study a congestion contour map was prepared, and in each study it was shown that the time-space relationship of congestion was greatly reduced.
5. On the John C. Lodge Project, a study was conducted in which driver comfort and service were evaluated as related to the freeway and alternate surface streets. It was found that as volumes approach capacity the freeway provides no more comfort or service than the surface street alternate route. In addition, it was found that the freeway becomes a less comfortable place to drive than the surface route as congestion begins to occur on both routes. From these findings it was concluded that, at least from the comfort and service evaluation, traffic should be diverted from the freeway to permit it to flow as freely as possible, and preferably, to maintain a near-capacity condition.
6. From a public relations standpoint, much less resistance was found in the Chicago study than in the Detroit study. This was because, even though this problem may not be a large one, it is still possible, and even probable, that the wrong person may be inconvenienced and cause a considerable amount of bad public relations. The problem is certainly reduced to a minimum when the ramps are metered and not entirely closed, because the motorist has a choice to make.

As mentioned in the report, the effect of ramp control on accidents was found to be favorable. However, it was pointed out that it would be premature to claim that accidents were significantly decreased as a result of this control. This implies that

further research needs to be done to document this finding on a statistical basis. I strongly recommend that studies of this type be initiated in Chicago as well as at other surveillance and control projects.

Since it has been shown in this study, and reinforced by the John C. Lodge Project, that this type of traffic control can substantially increase the capacity of a freeway, the question arises: "When should I install this or some similar system on a freeway in my state?" When I first became involved with freeway surveillance and control, I asked this question and soon found that the state-of-the-art is not such that this question can be easily answered. It probably will not be easily answered even after many more studies have documented the improvement of traffic flow with these systems. It is possible that a cost-benefit study can be made of any freeway to determine if it is economically feasible to install this or some other system. Although the cost-benefit study may indicate a favorable answer for freeway surveillance and control, many other factors must be considered before making a decision to install such a system. These would include a complete volume-capacity analysis of alternate surface streets and an evaluation of the enforcement, education, and public relation implications of the controls. However, the first consideration must be the availability and/or selection of an alternate surface street route for the motorist. Also, storage space must be available on the ramps being considered for metering. In addition, much more care must be taken in this decision since a considerably greater expense is incurred than with any other traffic control device now used. This implies that as these installations become standard, the location and design of freeways must take this into consideration. The first step toward this goal has been accomplished since the Bureau of Public Roads has shown willingness to participate in the design and installation of conduit for surveillance purposes.

Upon completion of several of these research projects, I am confident that ramp control, as well as other freeway traffic controls, will be found to be justified under certain conditions on an operational basis. When this step is reached and a decision is made to install such a system, it must then be decided who will operate these devices. As was mentioned, this decision will be made considering the three E's of traffic safety—Engineering, Enforcement, and Education—even though the decision may be made by a highway department. Therefore, the operation of such a system should continue to consider these three functions. This implies that management, on a policy-making level, should include representatives from each of these functions since the system will not function at a maximum level without the proper design, appropriate enforcement, and adequate driver education (public relations). This creates a problem since the education or public relation function has not been adequately established by law in most jurisdictions, whereas the engineering and enforcement functions are well established. This means that special care must be taken when choosing a public relations representative for this policy group.

The administration of such a system is appropriately a traffic engineering responsibility. This is particularly true when ramps are metered since changing the controls results from traffic engineering judgment based on an evaluation of various traffic measurements. Also, these systems, as set up for research and operations, have traditionally been administered by traffic engineers.

To summarize, this report has shown that metering traffic on freeway on-ramps will substantially increase volumes on the mainline while decreasing travel times for most motorists. This conclusion has been substantiated in other similar studies, such as the John C. Lodge Project in Detroit.

JAMES L. FOLEY, JR., Commissioner of Transit and Traffic, Baltimore—The 41,000-mile Interstate System includes approximately 6,700 miles of urban freeway, which amounts to about 16 percent of the system. It is expected that this 16 percent will have to carry 52 percent of the traffic.

It is obvious that the urbanized section cannot operate at the same level of convenience as the rural portion. The increasing shortage of adequate gaps in the mainline traffic stream requires the development of additional control techniques. The needfor these controls cannot be overemphasized.

In cities and suburban areas, expenditures of considerable amounts of money for traffic control to improve the operational characteristics can readily be justified when we look at the high cost of the land area requirements and the impact of the expressways upon the community. These factors make it obvious that it is impossible to construct all of the expressways which cities could use effectively.

The technique described in this report expands the capacity of the freeway by applying traffic control to one of the significant elements in the system. The report shows that even though significant benefits have been attained, additional investigations are still ahead of us and suggests areas of further research.

It was not too long ago that we felt we knew all of the answers. For example, adequate acceleration lane length was felt to be the solution to on-ramp problems. This report shows us how much we really do not know.

The successes of ramp metering emphasize the importance of preventing congestion build-up. Figure 5 of Mr. McDermott's report presents this relationship graphically. In a somewhat similar situation, invoking evening peak-hour restrictions on Calvert Street in Baltimore one hour earlier than the key demand resulted in lowered delays (shorter queues) to traffic one to one and one-half hours later.

There were several references in the study to use of only the five best operational peaks in each phase. This raises the question of why the analysis was limited andalso what the results might have been had all peak hours been studied, excluding perhaps those with known congesting events such as accidents.

Tables 1 and 2 show 20 to 25 days on which data were collected. Would the inclusion of all of these days have altered significantly the outcome or conclusion of the study?

Reference was made to the enforceability of the ramp control signals and the high level of obedience. The enforcement of such controls raises the question of techniques used by the enforcing officer. Stopping vehicles on the expressway for arrests could easily become an event which would reduce the capacity. The report does not indicate whether or not the control equipment presents a green indication to a waiting vehicle in the event that the preceding vehicle is waiting at the end of the ramp.

The expressway condition signs shown in Figure 3 are a technique which we can look to for the improvement of surface, as well as expressway, operations. Expansion of this technique could be a significant contribution to traffic operations and control. The report indicates that diversion characteristics were enhanced by this technique but does not set forth these results in measurable detail. Their use raises the basic question of how well the motoring public understood and used this device.

The improvements at the Austin bottleneck were felt to reflect seasonal variation; however, the Baltimore experience with the Calvert Street restrictions seems to suggest that perhaps the effect of metering downstream is a little more subtle and perhaps exerts greater influence than the measurements would indicate. Thus, metering ramps downstream may have improved the operation at Austin prior to the development of congestion. The effect may be as great or greater than the seasonal variation. This suggests the need for continued research to eliminate the seasonal variation.

In regard to daily performance variations, reference was made to random events. Are these events identifiable, or are they too minor and subtle? Missing dates in Tables 1 and 2 seem to indicate that, at least, major or catastrophic events were deleted.

The discussion of the effect of ramp controls on accidents indicates an area where further study could be fruitful. It is possible that this benefit could, in the long run, be the most significant gain resulting from improved expressway operation. It is assumed that the accidents cited were "reportable" accidents only. The 310 fewer ramp movements could possibly account for some of the reduced accidents. The motorists' acceptance of the "one-at-a-time" metering scheme is indicated by the obedience to the red signal. Does this technique extend to increased courtesy on the part of the mainline driver? This habit adjustment could reflect in reduced accident rates.

A surface street delay may not necessarily be real delay in that in many cases adverse trip length would be avoided. In the early days of Chicago's expressway system, many drivers went miles out of their way to take advantage of the Outer Drive even though the travel time was not reduced. As the short- to medium-length trips are discouraged from using the expressway, the lost time would be further decreased.

Mr. McDermott's report is another vote for continuous frontage road paralleling the expressways. This particular recommendation appears to be cropping up more and more frequently as experience grows.

The assumption of 2-minute increased travel time to diverted vehicles seems to be unduly severe. Inclusion of the calculation of this value would be helpful. It seems that this value is high when the total trip length is considered, inasmuch as expressway operating speeds of 25 to 30 mph do not have the high time-benefit over peak-hour surface operations that expressways have in the non-peak periods.

For the operating traffic engineer, the operational mode is the most exciting. There are presently thousands of miles of urban freeway which are at, or near, operational capacity. The ramp metering technique will make the operation of these facilities more efficient. The inability of even this tool to effectively handle special events such as accidents shows the need for additional types of control or advisory techniques to warn motorists of these problems. Expansion of the expressway sign system described would be one way of advising drivers. Automatic turn prohibitions at the beginning of ramps and advisory signs on the freeway upstream from the problem area could help unload the freeway during such events.

The report does not detail the alternate criteria used for the several control schemes. Of particular interest is the scheme which was apparently ineffective in anticipating the onset of congestion.

One general conclusion of the report is the implication that for maximum effectiveness, complete control of urban ramp systems is likely to be required or, at least, at those ramps feeding the expressway with volumes in excess of a certain value. It would be desirable if this study could determine what this volume level might be.

The inability of the ramp controls to completely solve the problem indicates that perhaps some form of speed control upstream on the mainline would render the ramp controls more effective. For example, automatic speed control, if used east of Austin, might adjust the arrival rate into the control section in a manner to allow greater volumes to enter from the ramps.

As in all good research projects, this study, in addition to answering many questions and providing tools and standards, also suggests additional areas to be examined. It seems that the system has reached a point where the operational mode could be installed in a number of cities for in-service testing.

DONALD G. CAPELLE, Traffic Research Engineer, Automotive Safety Foundation—Mr. McDermott has made a very convincing presentation of the benefits that can be obtained with freeway ramp control. Freeway congestion which results from peak traffic demands has become a widespread problem in all large metropolitan areas and the research presented by the author contributes significantly to the technology of freeway operations.

The use of more stringent controls to achieve satisfactory freeway operational requirements represents a valid approach to the improvement of freeway flow conditions. However, the effect that this control has on the adjacent street system must be reconciled. This is most evident from the author's comments on adverse control effects. His study reflects 10 vehicle-hours of ramp delay, which is very commendable when compared with the 186 vehicle-hours of delay saved on the freeway during the same time period. It would be interesting, although very difficult, to make a precise determination of increased vehicle-hours of delay on the adjacent major street system resulting from the ramp controls.

With the particular street system involved in the study, the delay problem on the streets adjacent to the freeway was apparently not aggravated to the extent that it was objectionable to the average motorist. However, this does not indicate that there was not a substantial overall increase in vehicle-hours of delay on the major street system.

The data resulting from this research show, unquestionably, that freeway operations can be vastly improved with a ramp metering control system. During all control studies, the severity of freeway congestion was significantly reduced with very little decrease in the number of through-put vehicles. This was accompanied by a reduction in the length of peak periods of flow and a 20 percent increase in the average speed of the traffic stream. This is a commendable increase in overall efficiency.

It is interesting to note, however, that the number of diverted ramp vehicles was not replaced by a similar number of freeway vehicles. As the author pointed out, maybe a more efficient ramp control system would permit a one-for-one exchange when ramp vehicles have to be diverted. This would provide an overall increase in the output of the system. It would be of interest to inquire further into why the present control system does not provide for this efficiency.

The accident data in Figure 17 show an overall reduction in accidents with the use of ramp controls. This is not surprising, since congestion and speed differential are two factors closely related to safety and a system which reduces the effect of these factors contributes to overall safer operation.

It appears from the plot of these accidents that the benefits of accident reduction are greatest in the freeway sections upstream from the control area. This can be attributed to the reduction in the upstream congestion. It is hard to comprehend, however, why there was not a similar decrease in accidents in the freeway sections within the control area.

Throughout the report, emphasis is placed on overall savings in vehicle-hours of travel time. This offers a good means for comparing different operations. It would appear, however, that an economic approach would provide a much more meaningful comparison. This type of data is very difficult to obtain, but when we as engineers become involved in projects which restrict the public from using facilities which were built with their tax money, we must be prepared to show the economic benefits that are accrued.

In closing, I would like to again commend Mr. McDermott for his development of a timely and helpful paper on the subject of ramp control. I am convinced that future operation of our freeways will require more and more control techniques similar to those developed in this paper.

JOSEPH M. McDERMOTT, Closure—The helpful suggestions and comments of the three discussions are genuinely appreciated, especially with regard to future research needs. While the research reported was concerned primarily with the operational effects produced through the automatic entrance ramp metering system, research has also been conducted and is continuing in such areas as economic analyses, system control theory, and demand-capacity, corridor relationships.

In this last research area, the Chicago Area Expressway Surveillance Project has been gaining metering experience in freeway corridors with network geometrics and entrance ramp demands quite different from conditions in the initial Eisenhower Expressway study section. In order to evaluate the effects of entrance ramp metering on traffic flows through various corridor configurations, the Project developed portable ramp metering equipment to expedite the conduct of short-term research studies.

The portable metering equipment features a pair of two-section, red-green, portable metering signals powered by standard 12-volt auto batteries. Auto headlight lamps serve as light sources in the signal heads; the interconnect between the two portable signals is accomplished by a radio-control circuit commonly used in model airplane applications. Ramp metering signal changes are triggered manually, by a technician

with a control button, at a pre-determined rate based on previous demand-capacity analyses of the freeway mainline. The technician can usually meter from a car parked on a frontage road adjacent to the ramp signals or from any other nearby inconspicuous vantage point.

Portable ramp metering equipment eliminates the commitment, expense, and installation time lag commonly associated with permanent operational signal systems. In two short-term research studies using four sets of portable metering equipment, the broad research objective of relating various corridor elements to the degree of ramp control was accomplished, while at the same time, the operational advantages of entrance ramp metering in a particular freeway corridor were demonstrated.

In November and December 1966, four entrance ramps on the inbound Dan Ryan Expressway were metered for research purposes with the portable equipment. The freeway corridor configuration was such that a significant reduction in expressway congestion was produced, while minimal adverse effects were transmitted to the surface streets. Inasmuch as these net operational benefits were even more obvious than those reported for the Eisenhower Expressway automatic control system, the Illinois Division of Highways requested continuation of the portable control on a daily basis when the short-term research study was scheduled for termination. Thus, daily peak-period entrance ramp control is now being maintained until a permanent, automatic, operational surveillance and control system is installed.

Although considerable freeway control system research undoubtedly remains to be undertaken, the Dan Ryan Expressway experience demonstrates that there are some freeway corridors suffering from inefficient distribution of traffic loads between the freeway and parallel alternates. There is no reason why ramp metering cannot be applied now as an operational measure in some locations. It can usually be expected that freeway operational improvements will result from entrance ramp controls whenever the entrance ramps cause the freeway overloading congestion problem. Careful preliminary corridor studies are needed, however, to establish that the net system benefits will indeed prove significantly positive.