An Experimental Measurement of Diversion Owing to Ramp Meters

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ABSTRACT

The effectiveness of ramp meters relates to the availability of alternative freeway or arterial routes, drivers' propensity to use these alternative routes and drivers' willingness to shift trips to alternative times of the day. Ramp metering, which is integral to Southeastern Wisconsin's regional traffic operations program, was evaluated for its effectiveness, including associated diversions of traffic. As part of this larger study, diversion was evaluated by performing a with-and-without meters experiment on a 15-mile corridor of US 45. This evaluation of diversion, primarily through statistical analysis of traffic counts on the freeway mainline, on parallel arterial streets and at on-ramps, along with analysis of origin-destination tables and a survey of Wisconsin drivers, indicates that ramp metering will divert traffic in very complex ways. Spatial diversion from the freeway to the alternative routes and from substandard ramps to a more desirable entrance took place within the studied roadway network. Slightly significant temporal variation is found, but the results were difficult to interpret as temporal diversion. Analysis of origin-destination tables showed that there was a reduction in very short trips. From the questionnaire responses, it was found that drivers knowledgeable about alternative routes were willing to divert to avoid delays.

INTRODUCTION

Ramp meters are a proven tool for managing freeway congestion. A critical component of ramp meter effectiveness relates to its ability to modify driver behavior. However, driver behavior responding to ramp metering is still controversial and is continuing to attract scrutiny because it affects the politics of deployment. One of the controversies is whether ramp meters divert traffic from the freeway mainline spatially, temporally and modally to improve the overall roadway network performance. Carefully controlled, empirical studies of ramp meter diversion are rare and very difficult to perform. Consequently, the amount and pattern of diversion from ramp meters is still not well understood, except as can be ascertained from applications of travel behavior theory and from psychometric studies.

Several recent simulation studies (1,2,3,4) have indicated that positive corridor traffic management benefits of time savings from ramp meters can only be achieved if there is considerable diversion from the freeway to adjacent arterials. A fairly recent, well-publicized, empirical study of ramp meter diversion was performed by the Minnesota Department of Transportation (Mn/DOT) (5), who conducted a study of the effectiveness of ramp meters in selected corridor segments in the fall of 2000 by turning off all ramp meters in the Twin Cities metropolitan area. The study concluded that there was some diversion to other time periods or different ramp entrances, and no significant diversion to different routes or other transportation modes. However, through random and corridor stated preference surveys when the meters were still on, the study found that about 70 percent of travelers stated they would use alternative routes to avoid waiting at ramp meters. This suggests that diversion should have been a very significant effect of turning off the meters, though significant spatial diversion cannot be concluded from the traffic data available within this study. Given that the empirical findings in Minnesota strongly disagreed with both the behavioral intentions of drivers and travel behavior theory, another look at the diversion potential of ramp meters seemed warranted.

Several older studies of the impact of ramp metering on parallel arterials have been conducted in Los Angeles, Denver, Seattle, Detroit and other cities. No significant diversion from the freeway to parallel arterials occurred in any of these locations (6). The Chicago Area Expressway Surveillance Project (7) undertook a ramp metering study on the northbound Dan Ryan Expressway. Ramp metering at just four ramps did not produce enough diversion to downstream ramps and/or surface street routes to completely prevent expressway overloading from occurring in the study section, but shifted the point of initial overloading upstream. It is unclear from the report whether parallel arterials were affected. One additional result relating to ramp meter diversion differs from the aforementioned empirical studies. Haj-Salem and Papageorgiou (8) conducted a field study of the corridor traffic pattern and the impact of ramp metering in the southern part of the Corridor Périphérique in Paris. The Corridor Périphérique consisted of two parallel rings around the city of Paris. The two rings were connected by a number of radial roads with corresponding on-ramps and off-ramps. The impacts of application of ramp metering were the ameliorations by 8.1 percent and 6.9 percent in total travel time for the two parallel rings including the ramps. There was an increase by 20 percent in total travel time for the radial roads, which addressed only 5 percent of the overall system travel demand.

The conflicting results about ramp meter traffic diversion behavior found in the literature introduce a great deal of uncertainty as to the benefits of ramp metering. Our study was initiated to determine whether significant diversion occurs when ramps are metered and to gain a better understanding of the types of actions drivers take when selecting alternative routes that might involve a ramp meter. An experimental design for the study was created to control for the presence or absence of ramp meters and to determine whether there was spatial diversion from the freeway to adjacent arterials, spatial diversion between ramps and temporal diversion from the peak hour to periods of time with less traffic.

Our study is primarily based on a rigorous collection of volume data both before and after the deployment of new ramp meters. However, additional evidence was obtained through a statewide survey of Wisconsin drivers and through analysis of origin-destination tables obtained by license plate matching.

EXPERIMENTAL DESIGN

Background

This study of diversion was part of a large project that identified methods for evaluating the effectiveness of ramp meters on Wisconsin freeways (9). The purpose of this larger study was to determine the benefits of ramp meters in the Milwaukee area freeway system, to determine underlying relationships that permit evaluation of new ramp meters or ramp meter systems elsewhere, and to develop a coherent framework for performing evaluation of ramp meter effectiveness on a whole system.

In order to assure that the conclusions are relevant to Wisconsin drivers and conditions on Wisconsin freeways, the research focused on data collected from the US 45 corridor, mostly in Milwaukee County, from three weeks before and three weeks after the deployment of seven new ramp meters in the southbound direction in early March 2000. This corridor spanned about 15 miles and included the freeway itself and two parallel arterials, Highway 100 and 124th Street (Figure 1). Both directions of the freeway were metered. This study was concentrated on the southbound direction because the deployment of new ramp meters was in the southbound direction. There were 14 on-ramps to US 45 (southbound) within the corridor, of which 13 were eventually metered. Interestingly, a single southbound on-ramp (Silver Spring Drive near the middle of the segment) was not metered during the entire study period. In the before period, only six on-ramps in the study area were not metered. In the after period, all on-ramps except the Silver Spring Drive on-ramp were metered. Highway 100 is a particularly logical choice of street for drivers wanting to avoid US 45 for trips in a southbound direction. The studied segment of Highway 100 runs from Silver Spring Drive to Lincoln Avenue, which is about 8 miles long and mostly has three lanes in each direction. The studied segment of 124th Street is from Silver Spring Drive to a point just south of North Avenue, which is about 5 miles long and mostly has two lanes in each direction. There are 13 major signalized intersections within the corridor.

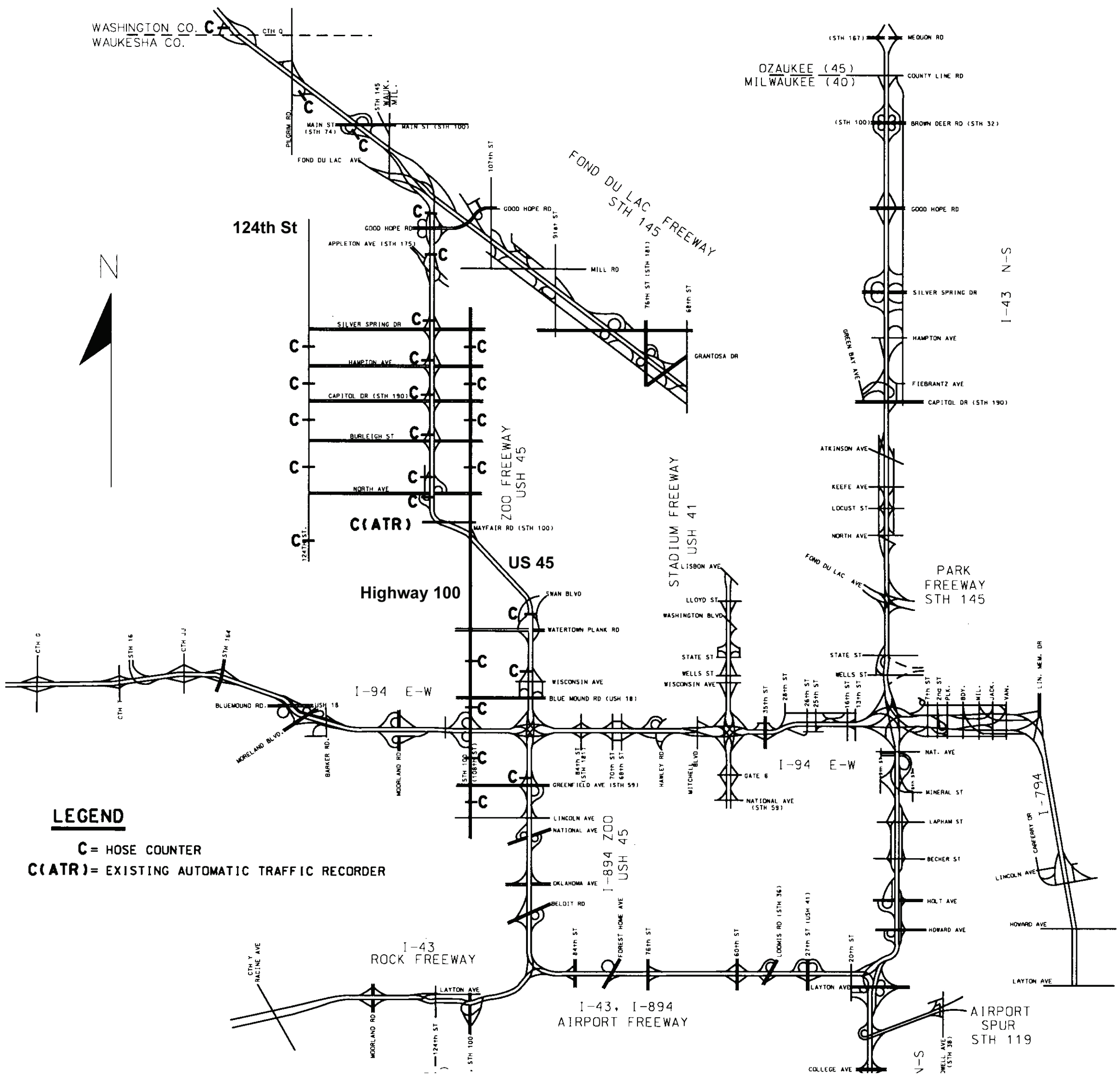

Figure 1 Study Area and Counter Locations

Data Collection

A comprehensive data collection, coordinating the efforts of Marquette University, the University of Wisconsin – Milwaukee and the Wisconsin Department of Transportation (WisDOT), resulted in precise snap-shots of the traffic conditions before and after deployment. Data collected included floating car runs, queue length counts, tube counts, origin-destination studies, questionnaires and archiving of a variety of loop detector data (volumes, speeds and occupancies). However, not all data were used for the diversion analysis, which depended primarily on traffic counts. Data related to traffic flow were collected on six weekdays (Tuesdays, Wednesdays and Thursdays) before deployment and six weekdays after deployment for 1 ½ hours in each of the morning and evening peaks. Data analyzed in this paper covered these items.

- Detector and Tube Counts. Count data from all loop detectors on US 45 were assembled. These loop detectors included mainline detectors for each metered ramp and other mainline detectors between ramps. In addition, counts were obtained from detectors located on the ramp (both at the top of the ramp, the "queue" detector, and at the stopline, the "passage" detector). Road tubes were deployed at all locations that could not be adequately counted by loop detectors: the southbound lanes of Highway

100 and 124th Street; all off-ramps; and all on-ramps without meters in the southbound direction of US 45.

- Origin-Destination Tables. Two tables giving the split of vehicles to each off-ramp from each on-ramp were obtained by video logging of license plates. The data for these tables were collected in 1999 and 2001, well before and well after the ramp meter deployment.
- A survey of Wisconsin drivers administered by the University of Wisconsin—Madison provided insights into drivers' route choices in reaction to ramp meter deployment.

WisDOT maintains 10 sets of mainline freeway loop detectors throughout the corridor. In addition, each ramp meter has its own set of loop detectors on the mainline. Thus, mainline volumes were available about once each mile in the test segment. Ramp meters operating in the before period already had loop detectors to measure entering volume. All on-ramps without meters in the before period and all off-ramps were fitted with tube counters. The possibility of inconsistencies between tube counts and loop detector counts was recognized but unavoidable. However, the same equipment was used to count traffic at each location in both the before and after periods, thereby reducing the significance of different types of equipment when making comparisons. Tube counters were placed on Highway 100 and 124th Street at about a 1-mile spacing. In total, 8 counters were placed on Highway 100 and 5 on 124th Street. In spite of the large number of counters and detectors, it was still necessary to estimate mainline counts at certain points in between mainline counters. In these cases, ramp counts were added or subtracted from either upstream or downstream (both, if possible) mainline counts to fill-in the missing data.

February and early March in Milwaukee are not good times to be collecting traffic data, and it was recognized at the outset that many data points would be lost. Because of many incidents, equipment failures and days with poor weather, it was necessary to limit the diversion analysis to three evening periods both before and after deployment of new ramp meters. The data presented in this paper are from days that were judged to be "incident free" with "good weather". The traffic count data are not sufficiently comprehensive to conduct an analysis of the patterns of diversion from the ramp meters, such as identifying specific routes. However, the data are sufficient to determine the existence of ramp meter traffic diversion behavior and the statistical significance of the diversion behavior. Consequently, conclusions from statistical analysis of two sets of data in this study should be tenable.

ANALYSIS OF DETECTOR AND TUBE COUNTS

Cutline Counts

Considering data availability and the likely traffic diversion patterns, eight cutlines are defined within the study corridor (Figure 2). Cutlines defined in this study are imaginary lines crossing corridor traffic in the study area. The cutlines are numbered 1 through 8 from the north to the south. The analysis of the traffic diversion from US 45 to the alternative arterial streets is then based on these eight cutlines. TABLE 1 lists the traffic counts passing these cutlines, which are averages of three p.m. peak periods in both the before and the after periods and are total vehicles per 1.5 hours for all of the lanes. Based on the before period, a positive diverted volume shows an increase of traffic in the after period, and a negative number shows a decrease. The percentage of diverted volume is also calculated based on the before period.

The pattern of diversion varied considerably depending upon the time of day and is highly complex, spatially. Generally, larger amounts of diversion (both to and from US 45) were seen in the later time intervals. The largest number of diverted vehicles from US 45 in a fifteen-minute interval is 165 (5:15 – 5:30 p.m.). The largest total traffic diverted in the 1.5-hour peak period is 333 vehicles. For Highway 100, the largest count increase in a fifteen-minute interval is 134 vehicles, and the largest total increase in 1.5 hours is 588 vehicles. In contrast, the result of Mn/DOT's study (5) shows an average decrease of just 56 vehicles per studied parallel arterial with the meters off.

Traffic diverted from US 45 is almost always less than 5%, agreeing with the results of Kang and Gillen's (10) that no more than 5-10% of vehicles will be diverted when ramp meters are turned on. However, traffic diversion resulting from ramp metering is not consistent between different cutlines. Even for one cutline, traffic diversion is not always consistent between different time intervals. A good example is cutline 8. Traffic on Highway 100 passing this cutline consistently increases more than 10% with meters on for all six fifteen-minute intervals. But traffic on US 45 passing this cutline only divert in three fifteen-minutes intervals and in the remaining three fifteen-minutes intervals traffic is attracted to the freeway.

In order to identify the statistical significance level of traffic volume differences observed on US 45 and the arterial streets in the before and after study periods, chi-square tests (contingency table analysis) are conducted. TABLE 2 shows the results from 48 chi-square tests based on traffic volume counts of three p.m. peak periods on each of the eight cutlines in each of the six 15-minute intervals. For nineteen of the interval-cutlines, traffic diversion resulting from ramp metering is statistically significant with a 95% confidence level (bold-faced). An analysis of variance on the same data produced similar results (TABLE 3). TABLE 3 deals with volumes at all cutlines during the six 15 minute intervals. These four factors were defined:

- Metered: before period; after period (2 levels)
- Cutline: #1, #2, #3, #4, #5, #6, #7, #8 (8 levels)
- Time: 1st 15 minute, 2nd 15 minute, 3rd 15 minute, 4th 15 minute, 5th 15 minute, 6th 15 minute (6 levels)
- Street: US 45, Highway 100, 124th St (3 levels)

Generally, there were three replications per cell; however, cells for 124th Street at cutlines 4-8 were empty for all periods and intervals. TABLE 3 summarizes the results for first order effects and second order interactions. Of greatest interest to this study are the effects and interactions that involve the “metered” factor. “Metered” is significant by itself and with “cutline” and “street”. It is not significant with “time”. Third and fourth order interactions were not interesting and have been omitted from this paper. This table is further evidence that spatial and temporal diversions are occurring because of ramp meters and is entirely consistent with the chi square tests.

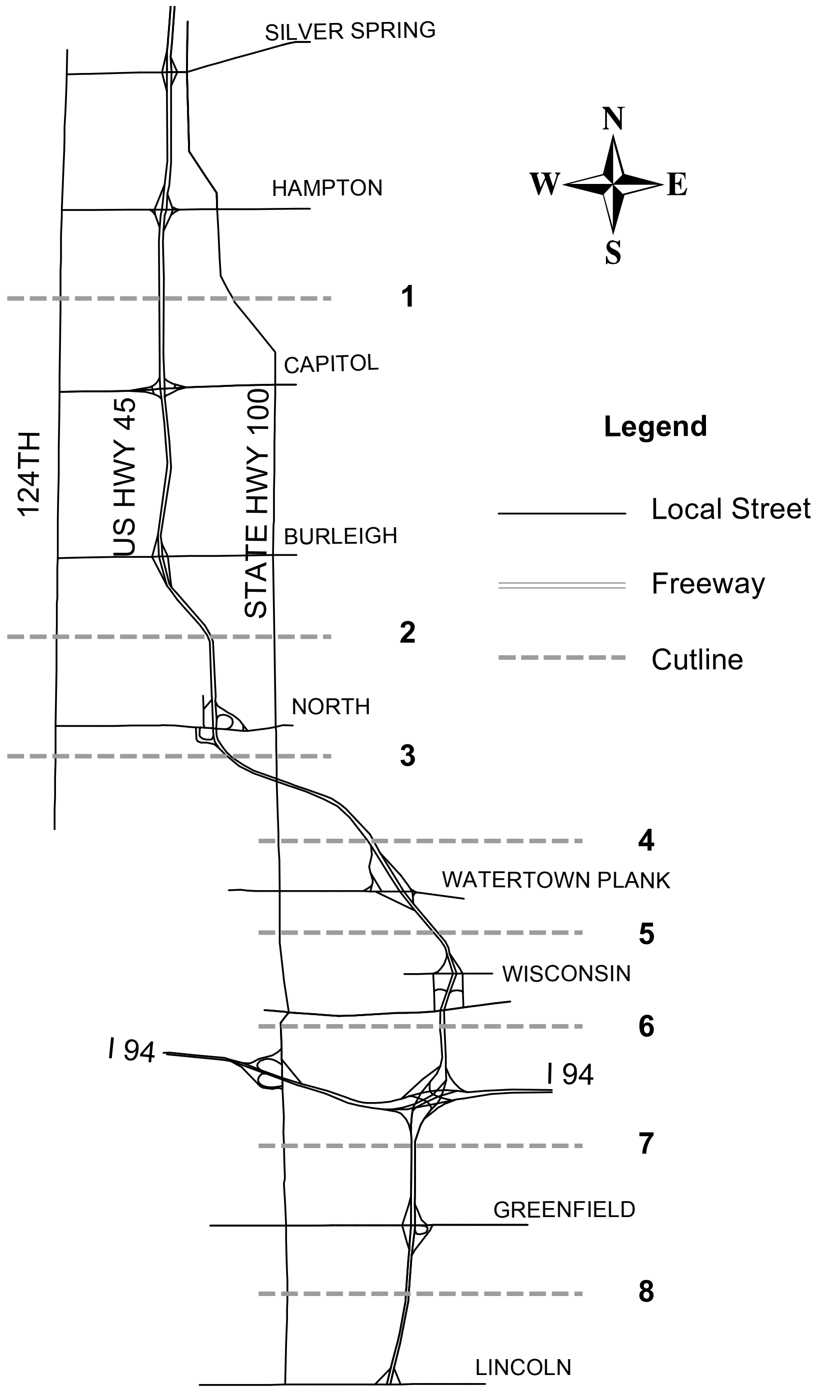

Figure 2 Diversion routes near US 45 and the Eight Analysis Cutlines

TABLE 1 Average Traffic Counts for the 1.5 Hour P.M. Period and Vehicles Diverted to Parallel Arterials

Cutline	124th Street				US 45				STH 100				Cutline Total Volume		
	Feb	Mar	Diversion	%	Feb	Mar	Diversion	%	Feb	Mar	Diversion	%	Feb	Mar	Difference
1	823	777	-46	-5.59%	7811	7751	-60	-0.77%	1119	1193	74	6.61%	9753	9721	-32
2	1440	1548	108	7.50%	8191	7858	-333	-4.07%	2411	2578	167	6.93%	12042	11984	-58
3	988	1009	21	2.13%	8667	8696	29	0.33%	2451	2616	165	6.73%	12106	12321	215
4					8302	8706	404	4.87%	2545	2655	110	4.32%	10847	11361	514
5					9593	9487	-106	-1.10%	2634	2693	59	2.24%	12227	12180	-47
6					10009	9834	-175	-1.75%	2989	3061	72	2.41%	12998	12895	-103
7					10503	10625	122	1.16%	2483	2756	273	10.99%	12986	13381	395
8					10116	10133	17	0.17%	2472	3060	588	23.79%	12588	13193	605

TABLE 2 Chi Square Tests of Diversion for the Eight Cutlines and Six 15-Minutes Time Intervals

	1st 15 Min		2nd 15 Min		3rd 15 Min		4th 15 Min		5th 15 Min		6th 15 Min	
Cutline	χ^2	df	χ^2	df	χ^2	df	χ^2	df	χ^2	df	χ^2	df
1	2.92	2	**9.11**	2	4.55	2	0.82	2	3.48	2	3.22	2
2	**8.02**	2	**15.78**	2	**6.67**	2	**9.36**	2	**9.80**	2	**19.38**	2
3	1.12	2	2.78	2	1.74	2	1.45	2	3.85	2	3.92	2
4	1.22	1	0.29	1	0.83	1	0.06	1	0.01	1	2.05	1
5	2.05	1	**4.51**	1	2.78	1	2.09	1	0.28	1	1.55	1
6	0.26	1	2.81	1	**7.51**	1	**4.58**	1	0.32	1	0.21	1
7	0.34	1	**18.46**	1	**7.52**	1	**11.49**	1	1.83	1	0.02	1
8	**10.14**	1	**38.98**	1	**15.22**	1	**51.18**	1	**17.99**	1	**19.71**	1

TABLE 3 Analysis of Variance of Cutlines

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	246017206	83	2964062.719	962.351	0.000
Intercept	312883609	1	312883608.8	101584.8	0.000
Street	209684346	2	104842172.9	34039.407	0.000
Cutline	7397175.528	7	1056739.361	343.095	0.000
Time	296992.095	5	59398.419	19.285	0.000
Metered	29373.936	1	29373.936	9.537	0.002
Street * Cutline	2532796.779	9	281421.864	91.37	0.000
Street * Time	1350198.158	10	135019.816	43.837	0.000
Street * Metered	40510.207	2	20255.103	6.576	0.001
Cutline * Time	251899.682	35	7197.134	2.337	0.000
Cutline * Metered	73128.537	7	10446.934	3.392	0.001
Time * Metered	17804.766	5	3560.953	1.156	0.330
Error	1848014.073	600	3080.023		
Total	735893348	684			
Corrected Total	247865220	683			

Dependent Variable: Volume

R Squared = .993 (Adjusted R Squared = .992)

Ramp Counts

Figures 3 and 4 show raw average ramp counts for all southbound on-ramps in the corridor for the 1st and 6th time intervals, respectively. Because of equipment problems, not all ramps had counts in both the before and after periods. In these figures, the absence of a bar denotes that there was no data available. Each bar represents between one and three days of data. Figure 3 shows the distributions of on-ramp traffic during the first 15-minute interval when traffic was lighter and ramp queues had not formed. In contrast, Figure 4 shows the distributions for the last (6th) 15-minute interval when traffic was heavier. While the after and before distributions in Figure 3 are almost identical, Figure 4 shows considerable differences. Most noticeably, traffic increased considerably at the Silver Spring Drive on-ramp, the only on-ramp in the corridor not metered. There also seems to be avoidance of the North Avenue on ramp, where the metering was unchanged. A similar result was seen in the 5th time interval and, to a lesser extent, in the 4th time interval.

Eight entrance ramps had complete data and were subjected to statistical analysis. Figures 5 and 6 illustrate the average traffic diverted on these entrance ramps in the same two 15-minute intervals for both the before and the after peak periods. TABLE 4 presents chi-square test results for all time intervals, indicating statistically significant results for only the last two intervals (bold-faced). An analysis of variance of the same data produced similar results (TABLE 5). TABLE 5 concerns the data used to draw Figures 5 and 6 and involves three factors. “Metered” and “time” are the same as above. The third factor, “location” refers to on-ramps and is defined as follows:

- Location: County Q, Pilgrim, Main, Silver Spring, North, Watertown, Wisconsin, Greenfield (8 levels)

The analysis of variance statistics, TABLE 5, show that “metered” was barely significant, but the interaction between “metered” and “location” is much stronger. Again, this result is consistent with the chi-square tests.

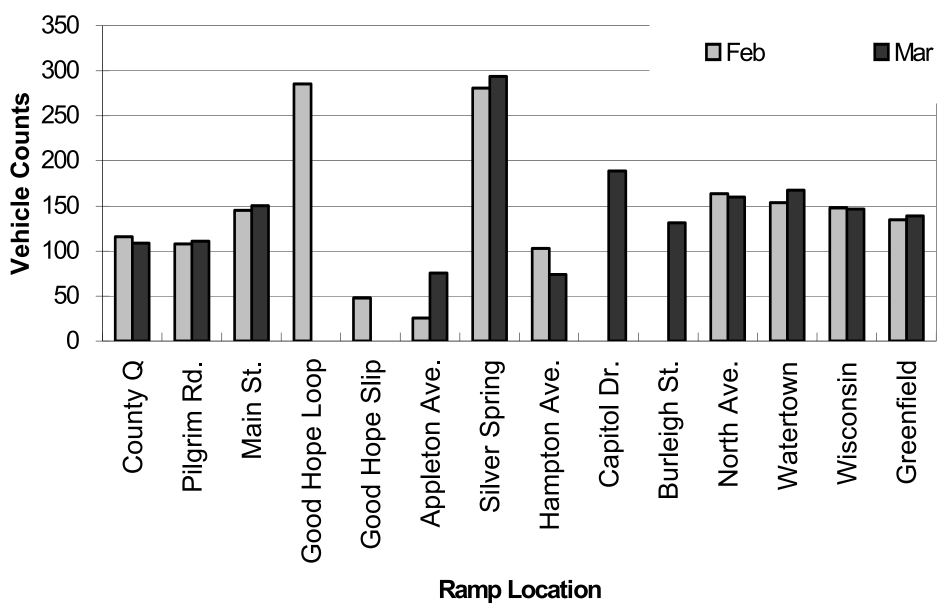

Figure 3 Average Ramp Counts for the First Time Interval

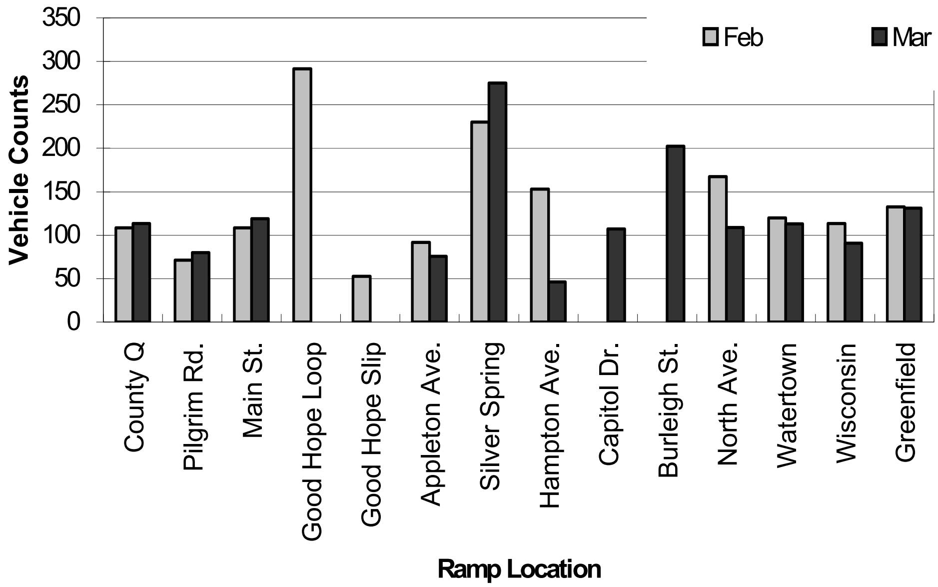

Figure 4 Average Ramp Counts for the Sixth Time Interval

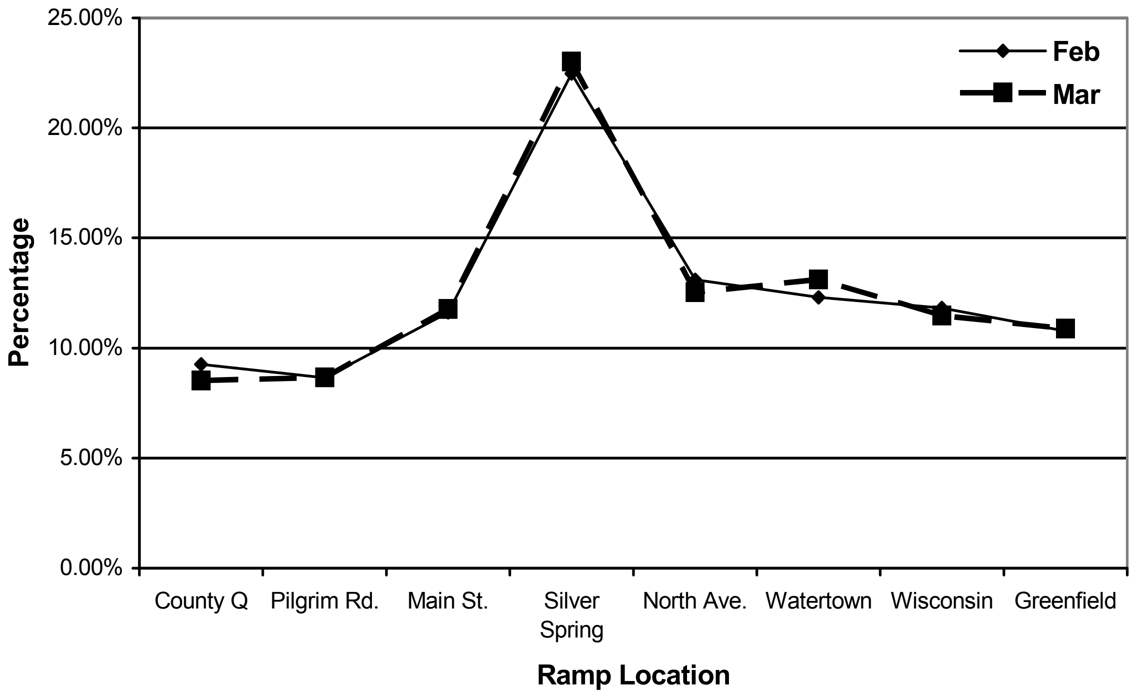

Figure 5 Average Ramp Count Percentages for the First Time Interval for the Eight Ramps with Complete Data

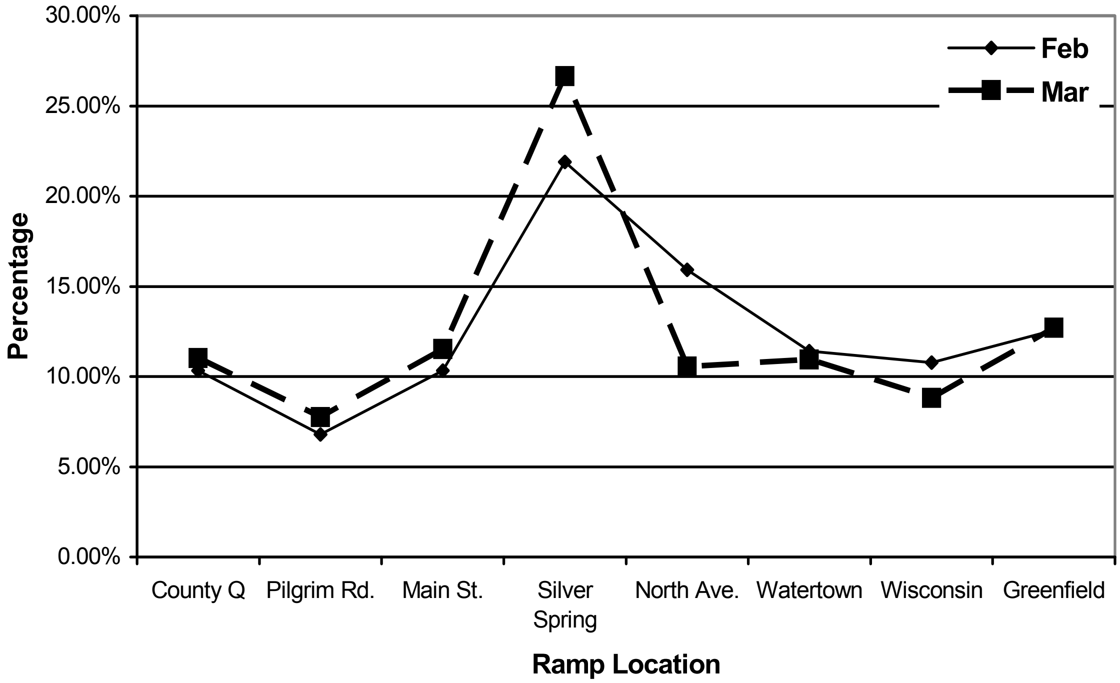

Figure 6 Average Ramp Count Percentages for the Sixth Time Interval for the Eight Ramps with Complete Data

TABLE 4 Chi Square Tests of Ramp Volumes for Six 15-Minute Intervals

15-Minute Intervals	χ^2	df
1	3.11	7
2	11.20	7
3	10.83	7
4	6.03	7
5	**25.67**	7
6	**59.10**	7

TABLE 5 Analysis of Variance of On-Ramps

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	940137.667	60	15668.961	36.048	0.000
Intercept	6549485.281	1	6549485.281	15067.724	0.000
Location	814048.302	7	116292.615	267.542	0.000
Time	67360.615	5	13472.123	30.994	0.000
Metered	1686.837	1	1686.837	3.881	0.050
Location * Time	43728.635	35	1249.39	2.874	0.000
Location * Metered	10703.302	7	1529.043	3.518	0.001
Time * Metered	2609.976	5	521.995	1.201	0.310
Error	98670.052	227	434.67		
Total	7588293	288			
Corrected Total	1038807.719	287			

Dependent Variable: Volume
R Squared = .905 (Adjusted R Squared = .880)

Temporal Diversion

The Mn/DOT's study (5) concluded that there was peak spreading when the ramp meters were turned-off, although it was difficult to see spreading effects in the data presented in the report. In contrast, we were unable to find any statistically significant peak spreading in the US 45 corridor. For example, Figure 7 shows the per lane volumes on US 45 for the after and before periods over 6 hours at cutline 4. The temporal distributions look almost identical. Similar results were seen at other cutlines. Figure 8 shows the whole corridor 15-minute counts at cutline 4. Although traffic increased between the before and after periods, the two lines are almost parallel, suggesting that there is no peak spreading. A comparison of Figures 7 and 8 shows that the freeway was not carrying any more traffic during the after period at this cutline, but the whole corridor was carrying more traffic.

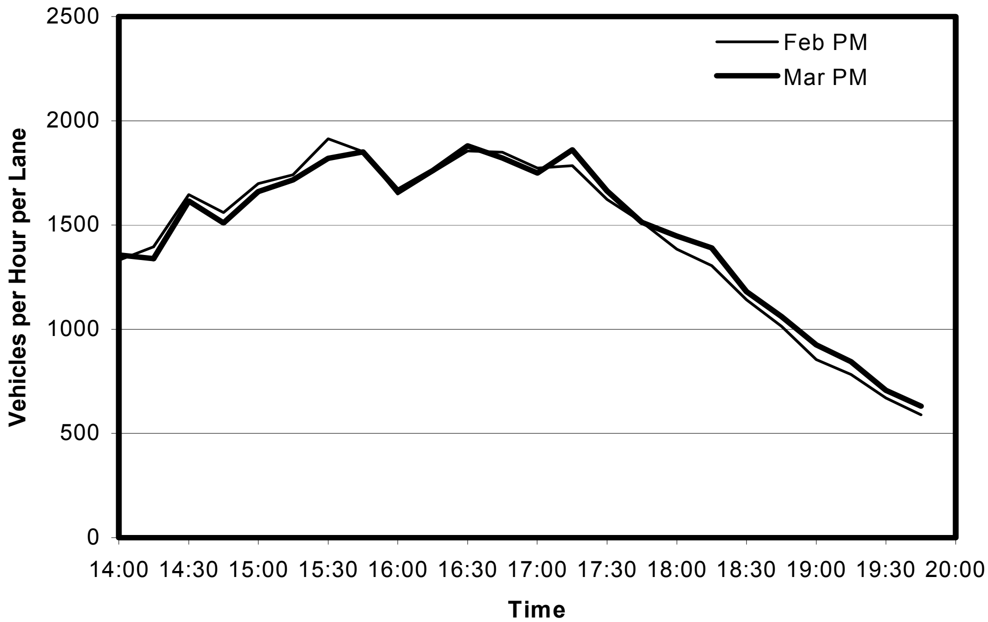

Figure 7 Per Lane Volume on US 45 at Cutline 4 over a Six-Hour Period

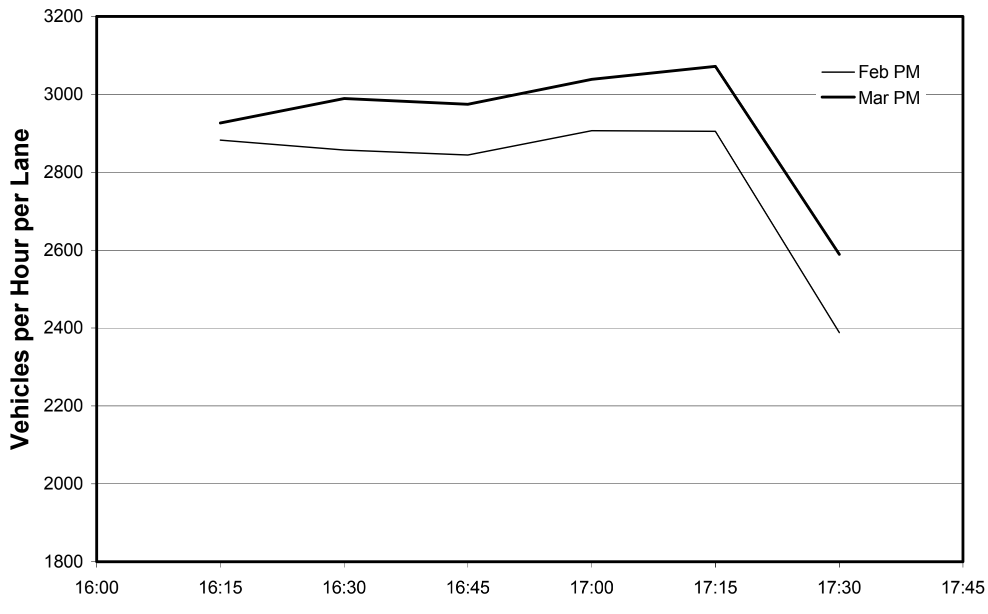

Figure 8 Whole Corridor 15-Minute Counts at Cutline 4 for the 1.5 Hour Period

Discussion

Spatial diversion from the freeway to the alternative routes and from substandard ramps to a more desirable entrance took place within the studied roadway network. Slightly significant temporal variation is found, but the results were difficult to interpret as temporal diversion. When attractive and efficient alternative routes are available, traffic will be diverted from the freeway to the alternative routes by ramp metering. Traffic will also be diverted to an entrance ramp where the delay is obviously less than other entrances. In this study, traffic is diverted from metered on-ramps to an entrance ramp without ramp metering. The largest number of diverted traffic from US 45 in a fifteen-minute interval is 165 vehicles. The largest total trips diverted in the 1.5 peak hours are 333 vehicles. Trips diverted from US 45 are almost always less than 5%. Not only can traffic be diverted from the freeway, traffic can also be attracted onto the freeway. In the after period, the largest increase of volume in 1.5 hours is 404 vehicles.

It is indicated in the study results that the deployment of ramp meters should be based at a corridor or system level, because drivers do react to recurrent delays at ramp meters and along freeway mainlines. The diverted 5% freeway traffic may be more than 100% of the existing traffic on alternative routes. The redistribution of ramp volumes between entrance ramps along freeway mainlines was sufficient to turn an already busy, unmetered ramp in an even busier ramp and to make meters at other ramps less congested.

ANALYSIS OF ORIGIN-DESTINATION TABLES

Two tables giving the split of vehicles to each off-ramp from each on-ramp were obtained by video logging of license plates. The data for these tables were collected in 1999 and 2001, well before and well after the ramp meter deployment. The data consisted of a percentage distribution of traffic from each on-ramp to all off-ramps. The percentages were multiplied by the before and after period on-ramp, peak-hour volumes to obtain estimates of numbers of vehicle trips between on-ramps and off-ramps both before and after metering. On-ramp to off-ramp distances were calculated from a scaled network of US 45. The data spanned US 45 from Pilgrim Road on the north to the I-94 interchange on the south.

The average trip length from the origin-destination tables increased from the before to the after periods. There was a 7% increase, from 3.861 to 4.127 miles, in the morning and a 4% increase, from 3.980 to 4.131

miles, in the afternoon. An analysis of a trip-length histogram showed that a contributing factor to this increase was a reduction in very short trips.

ANALYSIS OF SURVEY

A series of questions related to diversion from ramp meters was administered to a random sample of Wisconsin drivers as part of a larger study of variable message signs. A total of 221 valid questionnaires were returned. After eliminating any respondents who did not encounter ramp meters in their daily travel, there were 91 remaining questionnaires.

The average trip length across all valid respondents was 25.5 minutes. It is interesting that 72% drivers who encounter a ramp meter on a frequent trip are aware of an alternative route and 65% drivers have a good idea of how long that alternative route will take. TABLE 6 establishes a relationship between a driver's propensity to divert and the length of queue at a ramp meter. This question asks drivers for their stated preference and does not necessarily predict actual behavior. TABLE 6 suggests that drivers are quite sensitive to the length of the queue at the ramp meter, with only a few drivers stating they would divert even if there is no queue. Many of these drivers are probably already taking the alternative route. Nonetheless, there is a pattern in the data that suggests that drivers are more likely to divert when their trips are short. A larger sample size would be needed to validate this hypothesis.

The survey also shows knowledgeable drivers seem more willing to divert when the queue is long and less willing, almost unwilling, to divert when the queue is short. The data suggests that knowledgeable drivers are showing more strength (less neutral) in their route choice decisions. The results of this survey, although based on a small sample, are entirely consistent with our existing theories of route choice. Drivers with good knowledge of alternative routes are willing to divert to an alternative route to avoid waiting within a queue at a ramp meter.

TABLE 6 Summary of Responses from Diversion Questions

Queue Length Question (Shortened)	Percentage Indicating Yes	Average Trip Length for Drivers Who Divert (Minutes)	Average Trip Length for Drivers Who Do Not Divert (Minutes)
22a. Divert if ramp empty	15%	16.5	27.1
22b. Divert if ramp half full	24%	21.5	26.7
22c. Divert if ramp nearly full	62%	26.9	23.2
22d. Divert if ramp overflowing	82%	25.9	23.8

CONCLUSIONS

There are three common forms of diversion: spatial, temporal or modal. Modal diversion (such as shifts to carpools or transit) was not analyzed and there was no evidence in the collected data that temporal diversion (sometimes referred to as "peak spreading") occurred in the study corridor. Spatial diversion was ascertained by three different methods from the before and after data. Traffic counts indicated that diversion occurred between the freeway and parallel arterials, although not all times and not all cutlines were impacted the same. Statistically significant diversions away from US 45 occurred at times and places where traffic volumes were heaviest and ramp queues were longest. The data also revealed that there was diversion between on-ramps along US 45 in response to queuing at ramps. Analysis of origin-destination tables showed that there was a reduction in very short trips. From the questionnaire responses, it was found that drivers knowledgeable about alternative routes were willing to divert to avoid delays.

Drivers react to recurrent delays at ramp meters and along freeway mainlines when choosing between alternate routes. When faced with a long queue at an on-ramp, some drivers divert to another on-ramp while some others avoid the freeway entirely. The US 45 experience suggests that average trip length on the freeway increases when meters are deployed, thereby resulting in less entering or exiting for a given level of traffic on the mainline.

There should be further empirical investigations of diversion from ramp meters. These empirical investigations should include various methods of ramp metering, such as centralized control and decentralized traffic-responsive control. Empirical investigations should also cover a range of strategies for managing the length of queues at on-ramps.

This study could have benefited from data on specific route choices. Recent innovations in tracking vehicle trajectories with GPS might reveal subtle other effects that were missed by analysis of volume and origin-destination data.

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