Table 2. Temporal-spatial equity and mobility

			Travel Speed	Travel Time	Travel Delay
With Meters	TH169	Mobility Measures	62 km/hour	99 sec/km	68 sec/km
		Gini Coefficient	0.28	0.46	0.68
	I-94	Mobility Measures	79 km/hour	89 sec/km	42 sec/km
		Gini Coefficient	0.17	0.24	0.49
Without Meters	TH169	Mobility Measures	37 km/hour	113 sec/km	82 sec/km
		Gini Coefficient	0.23	0.21	0.28
	I-94	Mobility Measures	87 km/hour	75 sec/km	28 sec/km
		Gini Coefficient	0.14	0.16	0.39

Table 3. Productivity

		Segment VKT	VHT	Ramps VKT	VHT	Productivity (km/hour)
With meters	TH169	339822	3341	3994	703	85
	I-94	539286	5494	3785	264	94
Without meters	TH169	271388	5214	3815	95	52
	I-94	523027	5940	3819	95	87

Table 4. Accessibility measures

Model	TH169			I-94		
	With Meters	Without Meters	% Change	With Meters	Without Meters	% Change
$f(C_{ij}) = 1/t_{ij}^2$	2.9	2.5	16%	12.5	8.5	46 %
$f(C_{ij}) = e^{-0.00189 \times t_{ij}}$	58932	34502	71 %	42977	43597	-1.4 %
$f(C_{ij}) = e^{-0.08 \times t_{ij}}$	93.2	63.772	46%	822.5	456.9	80 %

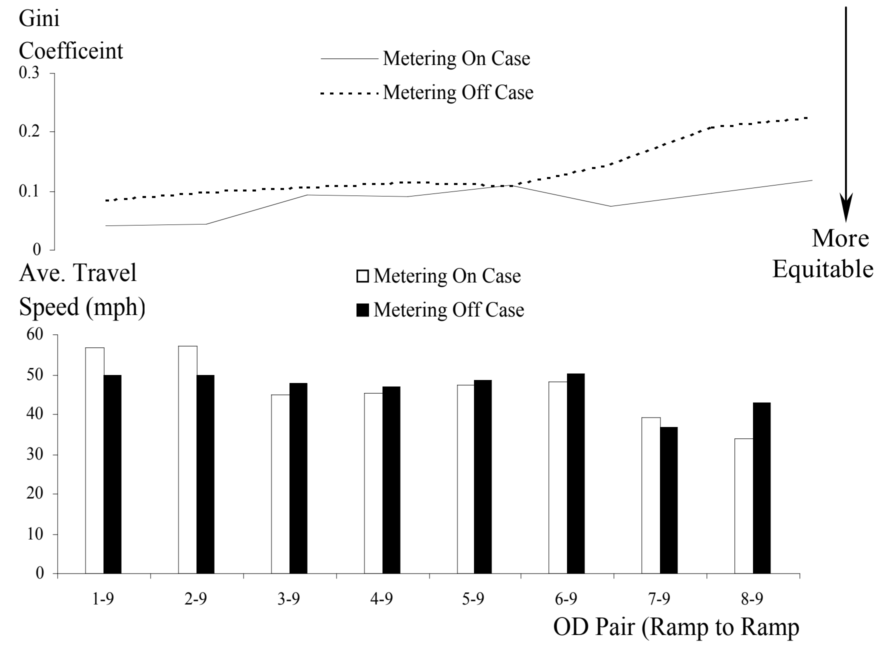

Figure 6. Temporal equity and mobility (speed) I-94

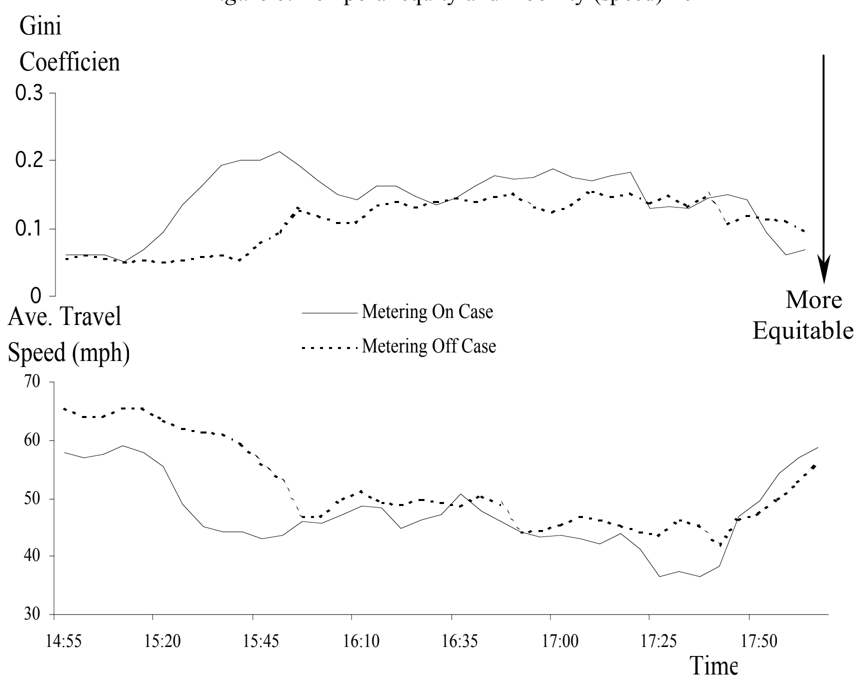

Figure 7. Spatial equity and mobility (speed) I-94

On I-94, there is an issue regarding the location of the study section. In the study section considered, metering rates were strict to minimize the formation of bottlenecks farther downstream. If these downstream locations and the ramps leading to them were accounted for in the calculation process, then there might have been variation in the results. However those data (particularly the ramp queues with metering) were unavailable.

4.1 Travel time variation

Inter-Day travel time variation results for one (TH169) of the four studied freeways are shown graphically in Figure 7 which is representative. It is obvious that for most OD pairs, inter-day travel time variability is reduced by implementation of the ramp metering system (null hypothesis $V_{off}–V_{on} > 0$ cannot be rejected at level 0.01). Freeway peak hour travel reliability increases with ramp metering. One can find that for extremely short trips (≤ 5 km), it is hard to say whether ramp meters improve or reduce travel time variations. Figure 9 illustrates intra-day travel time variation results with two curves representing metering-on and metering-off cases respectively. It is clear that ramp meters play a positive role in reducing intra-day travel time variation. Just as the inter-day results, intra-day travel time variation of long trips is reduced more significantly than those of short rips.

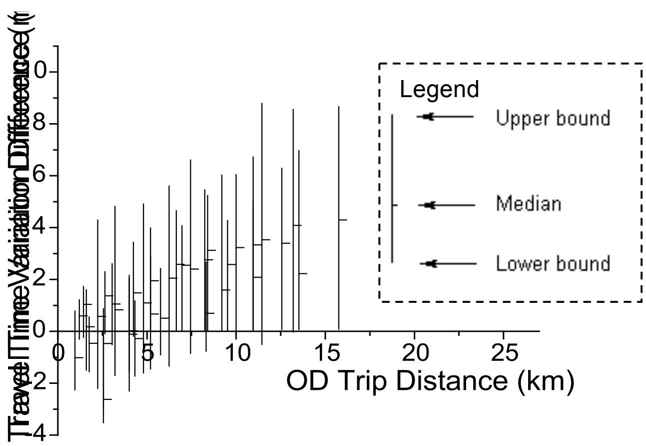

Figure 8. Inter-day travel time variation differences (Voff – Von) TH169

By assuming that all OD pairs have the same number of trips, overall average inter-day travel time variation differences can be obtained, which is 1.82 minutes. That means the implementation of ramp metering control can reduce 1.82 minutes of travel time standard deviation. Black and

Towriss1993 (13), Small 1995 (14) and Small et al. 1999 (15) estimated so-called "reliability ratio" (ratio of cost of standard deviation to mean travel time when scheduling costs are not separately considered) and consensus results of 0.7, 1.27 and 1.3 were obtained. Using the unit cost of travel time uncertainty — $0.21 per minute of standard deviation which was estimated by Small et al. (1999) (15) from a stated preference passenger survey in Los Angeles, CA, ramp metering in the Twin Cities can save $0.38 for each freeway trip in terms of increased travel certainty.

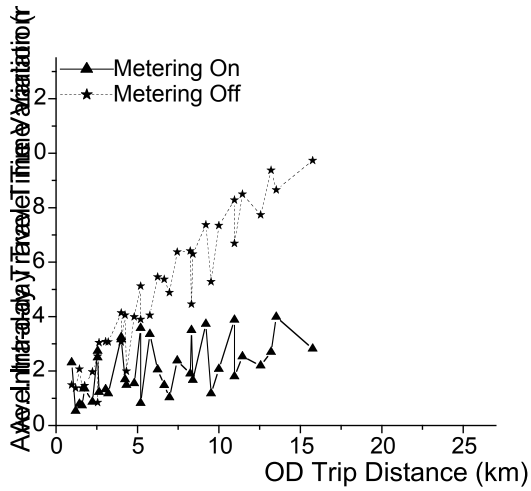

Figure 9. Intra-day travel time variation with/without ramp metering TH169

5. CONCLUSIONS

This chapter dealt with a number of measures of effectiveness. In general, the findings were favorable to ramp metering on TH169. These findings are limited in scope as they are based on only one representative day of each of the metering and no-metering period. Different sections change the results of some performance measures. Analysis of I-94 for instance, tempers some of the glowing results for ramp metering, suggesting a larger proportion of origin-destination (OD) pairs are worse off with meters than without, though other overall measures of effectiveness are still generally positive.

The theory underlying the Minnesota zonal ramp metering strategy argues that maximized flows on the freeway mainline guarantees lowest travel time for the whole freeway system including ramps. Following this logic, the ramp meters were intended to maximize throughputs at selected freeway bottlenecks. This study of TH169 shows that the facility performs better in the presence of operating ramp meters than in their absence, judged by a majority of the measures of effectiveness (MOE). The change in consumers' surplus was positive and the productivity of the system almost doubled. Freeway speeds and flows are consistently higher with ramp metering on than without. Furthermore, TH169 shows better trip speeds with metering. These gains by ramp metering are logical when the intention is to maximize freeway throughput. However, this metering objective does not necessarily maximize user satisfaction of the system due to unevenly distributed ramp delays. In contrast, I-94 shows improvements to the operations of freeway mainline do not always offset the additional ramp delay. Metering must be used finely with a chisel, rather than coarsely with a sledge-hammer.

Looking at the consistency of various performance measures developed in this chapter, it is found that mobility, consumers' surplus, productivity and accessibility tend to provide the same conclusions on the effectiveness of ramp meters. However, equity trades off with other MOEs. When ramp metering is present, long trips benefits while short trips are hurt, suggesting a more inequitable situation than without metering. If a ramp metering objective only pays attention to mobility (efficiency), its poor equity indications will inevitably lead to an important public policy debate — should we reserve the freeways for long trips. If the answer is no, a more refined ramp metering theory, which considers both efficiency and equity, is in order. Future theoretical studies should pursue alternative objective functions. For instance, efficiency can be defined more broadly as maximizing the utility of travelers, recognizing a non-linear value of time (one minute ramp delay is more onerous than one minute free-flow travel). A practical way to satisfy equity considerations is also suggested here: setting a constraint on individual ramp delay, even at the expense of overall freeway efficiency.

Any attempt to balance efficiency and equity of ramp meters must consider ramp delay in addition to freeway throughput. Unfortunately current data do not permit any such strategies. Aside from a few spotty locations, there exists no accurate measure of the number of vehicles waiting in queue at a ramp meter at any given time in the Twin Cities. This study attached here uses data from special data collection efforts carried out by Mn/DOT's Traffic Management Center on a few freeway facilities. Unfortunately, such data collection efforts are not routine. Additional data collection systems to measure queue lengths in real time are required.

Ramp metering was designed to improve freeway traffic flow and safety. While it generally does both, the analysis of travel time variation on all four studied freeways confirms that it also has the affect of improving travel time reliability for long trips. On average, ramp meters save $0.38 for each freeway trip in terms of increased travel certainty. Multiplying this figure by total annual peak hour trips, the resulting annual savings would exceed the monetized absolute travel time savings estimated in another parallel study

(16)[2]. This huge gain of more reliable travel should be captured in the analysis of ramp metering benefits.

Finally, it must be kept in mind that ramp metering alone cannot be expected to mitigate traffic growth. Given the under-investment in highway capacity relative to growth in demand, and the current unwillingness to affect demand through pricing or other measures, congestion is inevitable. While ramp meters can help at the margins, by delaying the onset of freeway breakdowns and making freeways flow smoother, they cannot eliminate congestion entirely.

NOTES

1. Alternatively freeway delay could have been defined as the difference between the actual travel time and the desired travel time (the travel time with the speed limit). In that case, reducing speed from 120 km/hour to 110 km/hour increases travel time, but still counts as zero delay, as the speed remains above the speed limit.
2. A discussion of safety effects of ramp metering is also provided in this reference.

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