Appendix K

Technical Memorandum: Secondary Research

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The purpose of this technical memorandum is to summarize the results of the secondary research task of the Twin Cities Ramp Meter Evaluation. This task involved reviewing and summarizing relevant research regarding the benefits and costs of ramp metering strategies employed in other comparable metropolitan areas. Included in this review and summary was the Texas Transportation Institute (TTI) ramp meter study titled "Ramp Metering in Minnesota" by Lomax and Schrank (1). In addition, two cities (Seattle, Washington and Phoenix, Arizona) were interviewed to obtain more detailed insight into the objectives, strategies, successes, and issues with their ramp metering systems.

Each section of this document contains the most recent information and trends regarding ramp metering and includes:

- Section 1.0 – Basics of Ramp Metering,
- Section 2.0 – Extent, Type, and Usage of Ramp Meters,
- Section 3.0 – Metering Goals and Strategies,
- Section 4.0 – Ramp Configurations,
- Section 5.0 – Measures of Effectiveness,
- Section 6.0 – Public Relations Efforts and Public Feedback,
- Section 7.0 – Enforcement Issues,
- Section 8.0 – Future Plans by Implementing Agencies,
- Section 9.0 – Keys to a Successful Ramp Metering Program,
- Section 10.0 – Keys to a Good Ramp Metering Study/Evaluation,
- Section 11.0 – Suggested Interviewees,
- Section 12.0 – Peer City Interviews, and
- Section 13.0 – References.

1.0 Basics of Ramp Metering

Ramp meters, sometimes called "merge lights," are traffic lights installed at freeway on-ramps metering each vehicle that enters the freeways by a certain amount of time. Without metering, vehicles usually enter the freeways in platoons, thus, creating turbulence at the freeway mainline. When the mainline traffic is already at or near its capacity, such turbulence causes even more adverse impacts. This turbulence causes stop-and-go traffic, which often leads to rear-end or sideswipe accidents. Simply put, ramp metering is "one proven method of maximizing existing roadway capacity" (1).

Depending on the type of the hardware, strategies used by the implementing agencies, and physical ramp/freeway/ alternative arterial configurations, the general benefits of ramp meters may include (1-8):

- Increases in freeway productivity, up to 2,700 vehicles per hour per lane (vphpl);
- Reductions in stop-and-go traffic;
- Reductions in sideswipe or rear-end accidents and fatalities;
- Reductions on impacts of recurring congestion due to heavy traffic demand;
- Reductions in fuel consumption from stop-and-go travel;
- Improvements in air quality and other societal goals;
- Delaying or preventing the occurrence of freeway slow speed operations;
- Breaking up of vehicle platoons;
- Promoting easier and safer merging from ramps;
- Reducing emergency or vehicle breakdown response time;
- Encouraging motorists on shorter trips to use arterials; and
- Encouraging motorists to shift travel times or change travel modes.

On the other hand, disadvantages of ramp metering include (1,2,4,7):

- Delays and increased emissions at the ramps – Although the overall travel time is improved and overall emissions are reduced, ramps experience increases in delay time and emissions. Furthermore, time spent waiting at the ramps is normally perceived to be longer, lowering its perceived benefits by the motorists (detailed in Section 5.0).

- Queues extending to the arterials – City agencies have worked hard to prevent such occurrences, because consistent interruption of local traffic will reduce the benefits of the ramp metering program. Depending on the geometric configuration of ramps and metering strategies used, this problem can be easily avoided (detailed in Sections 3.0 and 4.0).

- Higher volumes on the local arterials – Similar to the previous disbenefit, city officials often fear that the ramp delays encourage motorists to use the arterials, which is actually a desired effect for shorter trips. In fact, ramp metering is proven more effective when alternative arterials exist. Nevertheless, to gain support, standard agreements are often made between the highway agencies and local citizens/officials, limiting the traffic volume increases on the alternative arterials. The Oregon Department of Transportation (ODOT), for example, agreed that it would abandon the ramp metering program in Portland (OR) if the arterial volumes increased by 25 percent or more. Fortunately, this did not happen. In fact, studies in Portland and several other cities show that ramp metering did not create any significant traffic increases on the alternative arterials.

- Inequity issues – This is one of the main causes for public opposition to ramp metering. Ramp meters are believed be a disadvantage to citizens that are: 1) traveling on short trips without any alternative routes, and 2) living near the city centers, because freeway systems near the city centers are more likely to be congested, triggering the traffic-responsive ramp meters to impose higher delays. To gain public support, good educational efforts, along with certain compromises must be made (detailed in Section 6.0).

- Expensive – Costs of installation, maintenance, enforcement, and public relations of a ramp metering program can be high. The costs largely depend on the existing ramp geometry, selected controllers, and the extent of the ramp metering system.

- Accidents on the ramps – In Phoenix (AZ), installation of ramp meters caused a substantial increase in rear-end accidents (from two to 82 within six years) at the ramps, while the ramp meters were in operation. When not operating, the mere presence of the meters caused a significant increase in accidents at the ramps (from 34 to 76). However, mainline accidents decreased by 10 percent. Further study is recommended, since this phenomenon has not been well documented in other cities.

- Potential increase in single occupancy vehicle (SOV) use – A good, successful ramp metering campaign that dramatically improves freeway operations may encourage motorists to travel in SOV. But contrary to this opinion, Seattle experienced a 10 to 15 percent increase in HOV lane usage. While further study should be performed to gain conclusive evidence, implementation of ramp metering along with good corridor travel demand management (TDM) strategies may be able to discourage SOV.

- Encouraging longer trips – Along the line of the previous disbenefit, not only is the overall travel demand higher, motorists are also encouraged to travel longer trips.

2.0 Extent, Type, and Usage of Ramp Metering

Extent

By 1995, ramp meters had been installed and operated in 23 metropolitan areas in the U.S. Of these, 11 cities have a system of more than 50 ramp meters, including Minneapolis-St. Paul (Twin Cities) in Minnesota. Los Angeles (CA) has the most ramp meters, with over 1,000 meters in operation. Due to the overall positive benefits and publicized success stories, the number of participating cities is expected to only get larger.

System Warrant

Generally, there are no specific warrants for ramp metering, because of the many local factors involved. The Texas Department of Transportation (TxDOT) compares the peak sum of the ramp and all freeway mainline volumes to a preset table and determines if ramp metering is warranted at such location. Similarly, the Arizona Department of Transportation (ADOT) determines that the peak sum of the ramp volume and the right-most mainline lane volume must be equal or greater than 1,800 vehicles per hour (vph) to warrant ramp metering. If the rightmost mainline lane volumes are not available, ADOT uses the standard developed by TxDOT (7).

Historically, freeway sections that warrant ramp metering usually have the following characteristics (2,4):

- Peak-period speeds less than 48 kph (or less than 30 mph);
- Vehicle flows between 1,200 to 1,500 vphpl;
- High accident rates; and
- Significant merging problems.

Locations for Ramp Metering

There are three types of ramp meter locations (2):

1. **Arterial-to-Freeway Metering –** The most common ramp metering location to date, where ramp meters are installed on the on-ramps between city streets and the freeway.

2. **Freeway-to-Freeway Metering –** Ramp meters are placed on the ramp connectors between two freeways. This type of metering is less common and should only be adopted if there is ample storage room for the queuing vehicles, since freeways carry considerably more traffic than city arterials. Minneapolis-St. Paul and Los Angeles are the only two U.S. cities with extensive use of freeway-to-freeway ramp meters.

3. **Mainline Metering –** Technically, this should not be classified as ramp metering, since it meters the freeway mainline. This metering type should only be used upstream of severe geometric bottlenecks, such as bridges or tunnels, where infrastructure expansion is virtually impossible. More than just the travel time benefits, mainline meters help trucks avoid up-ramp stop-and-go movements on bridges and help improve emergency response times. Two tunnels in Virginia and Baltimore (MD) had mainline meters installed and resulted in positive benefits, but were removed due to public and political pressure. The Bay Bridge in Oakland (CA) has the only operating mainline meters in the U.S.

Controllers

Controllers are the software or logic that meters use in controlling the ramps. The oldest and simplest form of ramp meter controller is fixed-time, where equal delay is imposed on each vehicle no matter how good or bad the mainline condition is operating. On the other hand, new controller technology allows for more sophisticated metering, where metering can adapt to the changes in mainline and ramp traffic conditions.

There are five different types of ramp meter controllers (3,4,8):

1. **Fixed-Time Controller –** This most basic type of controller uses a fixed, pre-set metering rate, which usually ranges between four to five seconds. During the early years, police officers were stationed on the ramps to control the traffic. Relatively easy and cheap to install and operate, this control strategy is not flexible to significant changes in demands, or changes due to accidents/incidents.

2. **Local Traffic Responsive Controller –** This control strategy is directly influenced by the mainline and ramp traffic volumes. When the upstream and downstream freeway volumes are high, metering rates are automatically decreased (higher delays). Conversely, when ramp volumes are to the point where queues reach the city arterials, meter timings can be modified or eliminated. These rate adjustments usually occur about one minute after the data is collected. Generally, traffic responsive controllers result in five to 10 percent greater benefits than fixed-time controllers.

3. **Central Controller –** By centrally controlling the ramp meters within a network, traffic bottlenecks or accidents/incidents that occur several miles ahead can be detected, optimizing further the benefits of ramp metering. Furthermore, metering rates can be balanced among the ramps within the network, promoting equity. Many cities prefer centrally controlled ramp metering as it allows for more extensive monitoring, easier system override, and it improves performance of the transportation system. However, central controllers are very expensive and are more beneficial where recurring congestion exists.

4. **Integrated Controller –** In addition to detecting traffic conditions on the freeway network, the integrated controllers monitor traffic conditions on the alternative arterials. If traffic volumes on the city streets are too high, the meter delays may be reduced to encourage motorists to use the freeway instead.

5. **Fuzzy Logic Controller –** Traffic responsive controllers normally react to, rather than prevent congestion. As mentioned, traffic responsive controllers usually apply metering rates based on traffic data from the previous minute, which may be too late in the case of an accident/incident. Furthermore, traffic responsive controllers are not capable of interpreting erroneous or imprecise traffic data, which often occurs with freeway loop detectors. Fuzzy logic controllers manage to solve these problems by having short-range predictive capabilities, and can be utilized to smooth out and process imprecise or erroneous information.

Several cities, such as the Twin Cities, Seattle (WA), Denver (CO), and Detroit (MI), have adopted the centrally controlled ramp metering strategy. The remaining cities have installed the traffic responsive controllers. Of these, several still operate the ramp meters at fixed-time, due to public and political pressure (1).

During the Twin Cities evaluation effort, the University of Minnesota, with assistance from the Minnesota DOT, conducted a performance analysis of three selected algorithms (rules for operation of the meters) using a macroscopic simulation model with real freeway data. The study was called "Comparative Analysis of Operational Algorithms for Coordinated Ramp Metering" by Eil Kwon and Sreeman Nanduri at the University of Minnesota and Rich Lau and James Aswegan from the Minnesota Department of Transportation. Three algorithms were included in the study: 1) incremental group coordination (Denver, CO); 2) explicit section-wide coordination (Twin Cities); and 3) implicit coordination with fuzzy-logic approach (Seattle, WA).

The performance for each algorithm was analyzed using a simulation model developed at the University of Minnesota. Each of the algorithms were applied to the same freeway segment, a 16-mile section of TH 169 (northbound) which contains 28 entrance and 28 exit ramps. The travel data used for the analysis was collected during the ramp meter shutdown, October 17 and 24, 2000 from 2:00 pm to 8:00 pm.

The results of the algorithm analysis are summarized below:

- Incremental group coordination – Simple algorithm which does not require capacity estimates, resulted in more total congested vehicle hours than the other algorithms, and it is sensitive to detector malfunction.

- Explicit section-wide coordination – Consistently produced less total congested vehicle hours than other algorithms, resulted in more evenly distributed traffic over space and time, requires pre-determined bottleneck location and capacity estimates, and it needs accurate and reliable detection at key locations.

- Implicit coordination with fuzzy-logic approach – Algorithm does not require capacity estimation or pre-determined bottlenecks, less dependent on individual detector malfunctions, performance very sensitive to parameter changes, easy to adjust performance in real time by manipulating rules, and results in less congestion with compatible mainline vehicle miles.

Hours of Operation

In general, most ramp meters across the country operate during the a.m. and p.m. peak periods, which range between 6:30 a.m. to 9:30 a.m. for the a.m. peak, and 2:30 p.m. to 6:30 p.m. for the p.m. peak. Ramp meters with controllers other than fixed-time may turn on or off depending on the traffic volumes or occurrence of accidents/incidents. However, most agencies use standard hours to turn on/off their ramp meters, except in emergencies, for reasons of stability and reliability in the public eye. In San Diego (CA), for example, no manual intervention or ramp overrides are ever allowed.

However, several anomalies exist. In a busy, freeway-dependent city like Los Angeles, 32 ramp meters are operating at all times. As a result of a compromise between the Washington State Department of Transportation (WSDOT) and local neighborhood groups, a ramp meter in Seattle (WA) is only turned on during the p.m. peak (because fewer local commuters use the ramp during the afternoon hours). Due to equity issues, Detroit ramps that are close to the city centers are only metered in the off-peak direction. Another ramp meter in Seattle operates on weekends as well as weekdays.

3.0 Ramp Metering Goals and Strategies

Depending on the goals and objectives of the implementing agency, several types of ramp meter strategies can be pursued. Several factors influence how agencies choose the best strategy for their cities, but the decision is mainly driven by the public, local politicians, and geometric conditions of the ramps (detailed in Section 4.0). The types of ramp metering strategies include (1,5):

1. **Emphasis on Safety –** Under this scenario, safety is the main objective, and metering rates are typically very restrictive (imposing high metering delays). This reduces the traffic flow turbulence, and therefore the number of accidents at the merge areas. Often viewed as too restrictive and controversial, currently there are no agencies adopting this strategy.

2. **Optimize Travel Safety and Efficiency –** Metering rates are less restrictive, since some than Strategy 1 since some emphasis is placed on maximizing the capacity of the freeway. Minneapolis-St. Paul and San Diego are the primary cities implementing this strategy.

3. **Minimize Local Street Impacts –** When queue storage is limited on the ramps, as in the case of Houston (TX) and Arlington (TX), more provisions need to be made to ensure no queues develop on the arterials. However, such compromises decrease the effectiveness of ramp metering. Nevertheless, studies show that some positive benefits are obtained.

4. **Combination of Strategies 2 and 3: Basic Freeway Management –** Due to public and/or political pressure, most cities adopt this strategy as a compromise. Since the public is wary of queues and delay at the ramps, metering rates are adjusted at some cost to the freeway and overall transportation efficiency.

4.0 Ramp Configuration

Geometric Configuration

As mentioned in the previous section, the geometric configuration of the ramps is a key factor in deciding the ramp metering strategy. Since vehicles queue up at the ramps, ample storage room must be available. Increasing ramp storage capacity can be addressed using one of the following approaches:

- **Increasing the Length of the Ramps –** One simple way to provide more vehicle capacity is by increasing the length of the ramps. However, long ramps are expensive and space-consumptive. In urban areas, there is typically not enough room to build long ramps. Furthermore, long ramps may increase violation rates, especially if queues are constantly backed up to the ramp entrance.

- **Two-Lane Ramps –** Another simple way to increase ramp storage capacity is by adding another lane to the ramp. Similar to longer ramps, constructing a two-lane ramp can be an expensive and difficult effort, especially in urban areas.

- **High-Occupancy Vehicle (HOV) Bypass Lane –** When the on-ramp has two lanes, certain agencies prefer to dedicate one of the lanes as an HOV bypass lane, instead of metering both lanes. HOV bypass lanes are sometimes more attractive over two-lane ramp meters because they also promote carpooling and improve transit operations (4). The disadvantage of HOV bypass lanes is the possible increase in violation rates (6).

Experiences in Several Cities

The Minneapolis-St. Paul area has long, two-lane ramps that can store large numbers of vehicles. However, delays at the ramps have been known to be long, as high as 20 minutes. Interestingly, violation rates at these ramps remain low. Nevertheless, the Minnesota Department of Transportation (MnDOT) was able to implement Strategy #2 (Optimize Freeway Safety and Efficiency), largely because of the favorable ramp geometrics.

Conversely, most Texas freeways have frontage roads or arterials that parallel the freeways. Due to the close proximity between the frontage roads and the freeways, Texas on- and off-ramps are extremely short. Because of these unfavorable ramp geometrics, queues build up quickly at the ramps, jeopardizing traffic conditions on the arterials, which led the TxDOT to implement Strategy 3 (Minimize Street Impacts).

Other implementing cities tend to adopt a strategy that falls between Strategy 2 and 3, in part because of their ramp geometric configurations. Since modifying existing ramp configurations for ramp metering is not feasible in most areas, most cities work with the geometrics they already have. If an existing ramp is wide enough to safely accommodate an addition lane, most cities opt to install an HOV bypass lane.

Queue Detectors

If no further infrastructure improvements can be made and extensive queues consistently develop at the ramp, the implementing agency may: 1) increase the metering rates (lower meter delays) to quickly dissipate the queue, or 2) turn off the meters temporarily to flush all of the vehicles off the ramp. To accomplish this, queue detectors are necessary to detect traffic levels on the ramps. According to Havinoski (5), detectors are typically placed at the following locations:

- On the ramp, based on a fixed distance to the ramp meter stop line.
- On the ramp, based on a fixed distance downstream from the ramp entrance.
- Near the cross street, at the ramp entrance.
- On the frontage road, upstream of the ramp entrance – This configuration is more typical for ramps that are connected to the frontage roads, where the length of the ramp is short.
- Multiple queue detector configuration – In Seattle, ramp detectors are placed both in the middle of the ramp, as well as at the ramp entrance. The first set of detectors is used to increase the metering rates. If the queue still builds up and finally reaches the advance detectors, the meters can temporarily turn off to flush the queue off the ramp.

5.0 Measures of Effectiveness

Numerous evaluation studies have been performed on ramp metering systems throughout the world. Depending on the goals and objectives of each program, the measures of effectiveness (MOEs) used for each study are different. Table K.1 lists the MOEs that have been used, along with the trends caused by ramp metering.

Table K.1 List of MOEs

MOE	Trend
Freeway mainline speed	Increases
Accident rate/frequency	Decreases
Freeway mainline occupancy	Decreases
Overall travel time/delay time	Decreases
Freeway mainline volume/flow/stability of flow	Increases and stabilizes
Fuel savings	Increase
Benefit/cost (B/C) ratio	>1.0
Ramp delays	Increase
Arterial vehicle volume	Increases, but insignificant
Overall travel demand	Increases
Public/motorist survey results (qualitative)	Mixed

Source: 1-2.

Table K.2 provides a summary comparison of the Twin Cities evaluation effort to other ramp metering studies that have been conducted dating back to 1975. Where data was available, the table identifies the number of meters, type of control, metering strategy, hours of operation, and the various measures of effectiveness. The following conclusions have been observed from the studies:

- This study's finding of 22 percent savings in freeway travel time is well within the seven percent to 91 percent range observed in other areas (average of 25 percent travel time savings for 13 observations). The 22 percent travel time savings is also within the range of prior studies conducted on ramp metering within the Twin Cities (14 to 26 percent).

- Systemwide crashes for the Twin Cities increased by 26 percent without ramp metering. The average across eight other ramp meter evaluation studies reviewed by the evaluation team is 32 percent reduction in crashes. The range of values for reductions in crashes due to ramp metering is from five percent to 50 percent. In areas with more than 50 meters, the average crash reduction is 29 percent.

Table K.2 Comparison of Twin Cities Evaluation Findings to Other Ramp Meter Evaluation Studies

Location	Twin Cities	Abilene	Arlington	Atlanta	Austin	Denver
State/Country	MN	TX	TX	GA	TX	CO
Study Date	2000		1999	1996	1997	1982
Number of Ramp Meters in Study	431		5	5	3	28
Total Number of Ramp Meters	431		26	>50		
Type	Mostly central control, few fixed		Fixed, 4 sec cycle	Fixed		Central control
Strategy[1]	2		3	2-3		
Hours of Operation	Varies, peak period		6:15-8:30 a.m.	3:45-6:30 p.m.	a.m. peak	
Freeway Travel Time Impacts	-22%	-13%	-10%	-10%	-37.5%	-26.7% to -37%
Freeway Speed Impacts	+7 mph	+22%			+60%	+35.5 to +58%
Impact on Crashes	-26%					-5% to -50%
Traffic Volume and Throughput	+9% to +14%				+7.9%	+19%
Emissions Impacts	1,161 tons annually					+24%
Fuel Impacts	+22,000 gallons/day	-6%				
Benefit/Cost Ratio	5:1 to 15:1	62:1		4:1 to 20:1		
Average Ramp Delays	+2.3 min/veh					
Arterial Volume Impacts	Insignificant					+300 vph

Table K.2 Comparison of Twin Cities Evaluation Findings to Other Ramp Meter Evaluation Studies (continued)

Location	Detroit	Houston	Long Island	Los Angeles	Milwaukee	Minn-St. Paul
State/Country	**MI**	**TX**	**NY**	**CA**	**WI**	**MN**
Study Date		1997	1987 to 1990, 1991	1975	1995	Several, 1975 to 1996
Number of Ramp Meters in Study	28		60	259	6	Varied
Total Number of Ramp Meters	49	<50	75	808	43	431
Type	Central control	Fixed	Traffic responsive and central control	Traffic responsive	Traffic responsive and central control	Mostly central control, few fixed
Strategy[1]		3		2-3	2-3	2
Hours of Operation		6:30-9:30 am, 3:30-6:00 p.m.		Varies, 32 all day	Varies, 6-9 am, 3:00-6:30 PM	
Freeway Travel Time Impacts	-7.4%	-22%	-13% to -20%	-13%		-13.8% to -26.5%
Freeway Speed Impacts	+8%	+29%	+9% to +21%	+15 mph	+3% to +35%	+14% to +60%
Impact on Crashes	-50%		-15%	-20%		-24% to -29%
Traffic Volume and Throughput	+14%		0% to +7%	900 vpd	+22%	+8% to +40%
Emissions Impacts	124,600 tons annually		+17.4% CO, +13.1% HC, -2.4% NOx			2.2 million kg annually
Fuel Impacts			-6.7%	-13%		
Benefit/Cost Ratio						7.3:1
Average Ramp Delays			1.2 to 3.4 vehicles			0.1 to 2.5 minutes
Arterial Volume Impacts	Insignificant			Insignificant		

Table K.2 Comparison of Twin Cities Evaluation Findings to Other Ramp Meter Evaluation Studies (continued)

Location	Phoenix	Portland	Sacramento	Seattle	Zoetemeer	M6 Motorway
State/Country	**AZ**	**OR**	**CA**	**WA**	**Netherlands**	**England**
Study Date	1989 to 1995	1982	1984	1981 to 87	1995	1986
Number of Ramp Meters in Study	9	16	9	22	9	1
Total Number of Ramp Meters	121	58	19	105		
Type	Fixed	Fixed	Traffic responsive	Central Control, fuzzy logic		Fixed
Strategy[1]	2-3	2-3	2-3	2-3		
Hours of Operation	5:30-9:00 a.m., 2:30-6:30 p. m.	6:30-9:30 a.m., 3:00-6:30 p.m.	7:00-9:00 a.m.	6:30-9:00 am, 3:00-6:30 p.m.		
Freeway Travel Time Impacts		-7.4% to -39%		-47.7% to -91%	-13%	
Freeway Speed Impacts	+5 to +10%	+7.5% to +155%		+20-25%	+15%	
Impact on Crashes		-43%	-50%	-38%		
Traffic Volume and Throughput	+15%	+25%	+3% to +5%	+62% to +86%	+3%	+3.2%
Emissions Impacts						
Fuel Impacts		540 to 700 gal/day				
Benefit/Cost Ratio	5:1 to 10:1			10:1 or more		
Average Ramp Delays				< 3 min	+20 sec	+1.5 min
Arterial Volume Impacts				Insignificant		<5% diverted from fwy

[1]Metering Strategies: 1 = Emphasis on safety; 2 = Optimize Travel Safety and Efficiency; and 3 = Minimize Local Street Impacts.
Abbreviations: sec = seconds, min = minutes, hrs = hours, mph = miles per hour, vph = vehicles per hour, HOV = high-occupancy vehicle, VMT = vehicle miles traveled, fwy = freeway, veh = vehicle, kg = kilograms.

- This evaluation shows that there is a 14 percent increase in freeway throughput due to ramp metering. The average for the 12 other studies reviewed by the evaluation team is 18 percent, with a range from zero percent to 86 percent. Long Island, Phoenix, Portland, and Seattle (cities with more than 50 meters) show an average of 38 percent increase in freeway throughput.

- Other evaluation studies have limited impact information related to emissions impacts of ramp metering. Three other metropolitan areas (Denver, Detroit, Long Island), which evaluated emissions as part of their ramp meter study, showed some improvement in overall emissions due to ramp metering. Long Island showed a 6.7 percent increase in NO_x, and the improvements in CO and HC of 17.4 and 13.1 percent, respectively.

- Four areas which evaluated fuel consumption impacts of ramp metering showed savings due to ramp metering ranging from about six percent to 13 percent. However, as mentioned in Section 7.0 of this report, the fuel consumption analysis used in this evaluation used a simple straight-line estimation technique which does not address the tempering of flow typically due to ramp metering, by smoothing the travel speed variability (less acceleration and deceleration).

- There is limited information on benefit/cost ratios of ramp metering evaluations. This current study's benefit/cost ratio of 5:1 for the entire congestion management system and 15:1 for the ramp metering costs only are within the ranges seen for other areas. For five areas (Abilene, Atlanta, Phoenix, Seattle, and previous Minneapolis/St. Paul evaluation efforts), the range of benefit/cost ratios is from 4:1 to 62:1, with an average of 20:1.

■ 6.0 Public Relations Efforts and Public Feedback

Most quantitative studies and evaluation results show that ramp metering has achieved numerous positive benefits, including reduced travel time and accident rates. However, these are benefits quantified and seen by the implementing agencies, but the results are often not communicated to the public. Like most other public works projects, the citizens are the customers, and to ensure the success and/or longevity of these projects, customer understanding and satisfaction are important.

In fact, city agencies believe that support from the public and local politicians are crucial to the success of ramp metering. Some of the public relations (PR) efforts that have been done in various implementing cities are listed below (1-3):

- Support from local politicians.
- Positive reviews from local media.
- Public meetings and input sessions.
- Publicity (media, ads, brochures, billboards, free keychains/pins, etc.).
- Educational efforts (free videotapes and classes).
- Compromises and agreements – As in the case of Portland (arterial volumes not to increase by 25 percent or more), Seattle (one ramp activated only in the p.m. peak, lower meter delays near downtown), Detroit (metering the downtown ramps only in the off-peak direction), and Milwaukee (equal metering rates within the network).
- Catchphrases – Coin slogans that are easy to understand and remember, and highlight certain benefits/solutions to problems that citizens would like to have. For example, New York City (NY) calls their ramp meters "Merge Lights," stressing the safety benefits of ramp meters in the merging areas. Houston launched a publicity campaign with the catchphrase "Go With the Flow," highlighting the travel time benefits of ramp metering.

The following highlights some of the typical customer feedback from users of ramp metering systems (1):

- In Portland (OR) and San Jose (CA), citizens saw positive results and tangible benefits from ramp metering. In both cases, the positive reviews came from highly publicized benefits of ramp meters and public surveys performed by the local media.
- In Houston (TX), the public was split between realizing the "positive benefits" and "no real change" of ramp metering. This was largely due to the short ramps, which forced TxDOT to adopt the least beneficial strategy (detailed in Section 4.0).

- In the Twin Cities (MN), the public generally had positive perceptions towards ramp metering, but it has been declining. Mainly, citizens realize benefits of ramp metering, but think that the ramp delays are too long. Interestingly, violation rates still remain low at these ramps. Again, because of the strategy chosen by MnDOT (#2 – Optimize Travel Safety and Efficiency), the ramps are set to be more restrictive, while realizing additional delays at the ramps.

7.0 Enforcement Issues

Newman et al. (6) indicate that a good ramp metering enforcement strategy can result in violation rates as low as five percent. Generally, it is imperative to keep violation rates below 10 to 20 percent, otherwise public trust may start to deteriorate. The following lists a few reasons why compliance rates may tend to drop (1,2,6):

- **Lack of police enforcement –** Since police officers are often needed to respond to emergency calls, consistent police enforcement is difficult and expensive.
- **Diminished returns –** Over time, the public may lose their perceptions on the benefits of ramp metering, as experienced in Minneapolis-St. Paul.
- **Presence of HOV bypass lanes –** Since freeway HOV violation rates tend to be high, motorists may be reluctant to comply with HOV bypass lane regulations.
- **Technical problems –** Public trust can deteriorate significantly if ramp meters experience technical breakdowns on a frequent basis. Also, since the ramp metering controllers are date- and time-sensitive, agencies must remember to adjust for daylight savings time changes.
- **Extensive ramp delays –** Although no studies have been performed to prove this hypothesis, long delays are expected to increase violation rates.
- **Light punishment –** Again, no studies have been done to support this suggestion, but light punishment may tempt motorists to violate more often. Newman et al. (6) believed that "an increased fine might help to offset some of the expense of police enforcement, while a more publicized penalty might reduce violations."

The following lists some ramp meter enforcement strategies that have been implemented by various agencies across the country (6):

- **Consistent police enforcement –** Though costly, police enforcement is the most effective enforcement strategy.
- **Video enforcement –** Video enforcement may not be a very accurate method of enforcement, due to high false-identification rates. However, the presence of video cameras may deter motorists from violating.
- **Reporting system –** In Seattle, WSDOT launched the "HERO" program, which allows motorists to report violators via a toll-free number. The violators will then receive warnings by mail. Initially, the program resulted in a significant reduction in the violation rate. Over time, however, as violators realized that no further action would be taken, the program lost its effectiveness.

8.0 Future Plans for Ramp Metering Systems by Implementing Agencies

Below are some of the future goals set by several transportation agencies, to continuously improve upon their existing ramp metering program (1):

- **Install more meters –** Cities with small to medium-sized ramp metering programs usually set this future goal, a clear indication that the existing program has achieved a certain level of success and acceptance in the eye of the public.

- **Install centrally controlled meters –** Cities with fixed or traffic responsive controllers plan to install centrally controlled systems to achieve greater benefits through this more efficient and extensive ramp metering program.

- **Upgrade computer systems –** Denver, which already has a centrally-controlled ramp metering system, hopes to upgrade its computer hardware and software systems. The upgrade is expected to make the program more effective and efficient.

9.0 Keys to a Successful Ramp Metering Program

Based upon the secondary research, the following lists some of the strategies for a successful ramp meter program.

- **Select the right place –** In order to realize significant positive benefits of ramp metering, it is necessary to implement ramp metering in freeway sections that actually need it. As discussed in Section 2.0, appropriate locations typically have the following characteristics: peak-period speeds less than 30 mph, flow of 1,200 to 1,500 vphpl, high accident rates, and significant merging problems.

- **Secure funding –** Before embarking on a ramp metering program, make sure that the local politicians and city officials are committed to funding the program. In some cases, public-private partnerships can forge a more secure funding situation.

- **Start small and simple –** Cities trying to implement ramp metering for the first time should start with a few ramps, with a fixed-time control, adopting a more conservative strategy (Combination of Strategy 2 and 3 – Basic Freeway Management, or 3 – Minimize Street Impacts).

- **Excellent public support –** All implementing cities believe that public education and support are critical to the success of their ramp metering programs (detailed in Section 6.0).

- **Ample storage capacity –** Most cities would like to have longer and wider ramps, to prevent queues from extending beyond the ramps, onto the arterials. If long queues with backups onto the arterials occur on a consistent basis, good queue detection systems, and adopting a more conservative strategy (Strategy 3 – Minimize Street Impacts) may be necessary (detailed in Section 4.0).

- **Synergy –** Use other forms of Intelligent Transportation Systems (ITS) to eliminate disadvantages found in ramp metering alone (i.e., ramp delays or increases in arterial volumes). Agencies may couple ramp metering with ramp queue wait time signs or an Advanced Traveler Information System (ATIS) that can inform motorists of crowded ramps, or provide motorists with options of different travel modes, times, or routes.

- **Avoid conflicting solutions –** Mainline freeway HOV lanes and ramp meters are two freeway management solutions that may not work well together. In some cases, mainline HOV lanes are believed to dilute the benefits of ramp metering (3). Without HOV bypass lanes or direct HOV connectors, metering may impose unnecessary delay to buses and carpools.

- **Eliminate technical problems –** Make sure the system is free from technical breakdowns, to sustain high public trust and compliance rates (detailed in Section 7.0).

- **Consistent enforcement –** A study by Newman et al. (6) showed that consistent police enforcement, though costly, is the most effective enforcement strategy (detailed in Section 7.0).

- **Continuous improvement –** Upgrade the fixed or traffic responsive controllers to central or fuzzy logic controllers. Central control offers greater benefits because it can monitor an entire system, while fuzzy logic controllers eliminates the possibility of processing and applying imprecise or erroneous traffic data (Section 2.0).

■ 10.0 Keys to a Good Ramp Metering Study/Evaluation

Based upon the secondary research, the following summarizes some of the strategies agencies can use to obtain a successful ramp metering evaluation study.

- In an area where ramp meters have been in operation for a long period of time, a "without ramp metering" study may be necessary. If the area has experienced significant changes over the years ramp metering has been in place, using the "before ramp metering" data collected prior to deployment is unlikely to be relevant with today's conditions.

- Since fixed-time ramp metering is believed to be a disbenefit for freeway sections that are not congested (by unnecessarily delaying motorists at the ramps), these meters may be deactivated temporarily, to study the differences in benefits.

- When comparing evaluation results from other areas with ramp metering, consider that the differences in benefits can be attributed to:

  – Strategy adopted,

  – Ramp geometric configuration,

  – Population/population growth,

  – Freeway lane miles,

  – Travel rate index – measure of additional time required to complete a peak-period trip compared to the same off-peak trip,

  – Travel delay per person – measure of time wasted each year in hours by each person in the urban area due to heavy traffic, and

  – Roadway congestion index – traffic density measure showing relationship of vehi cle-miles of travel to lane-miles of roadway. When this index reaches 1.0, the roadways in the urban area are considered congested at an area-wide level.

- A good ramp metering study/evaluation effort should possess the following characteristics:

  – Short intervals for data collection (20 seconds to 15 minutes),

  – Long duration (at least several weeks),

  – Automated data collection effort as much as possible,

  – Studies of travel behavioral changes, especially the use of alternative arterials/ routes/modes/travel times,

  – Study of accident rates at the freeway mainline, as well as on the ramps,

  – Analysis of a larger study area (to determine systemwide benefits/costs),

- Analysis of travel time versus waiting time versus perceived waiting time, and
- Analysis of the benefits and costs using local data, instead of national data (i.e., local value of time, inflation, etc.).

■ 11.0 Suggested Interviewees

Case studies of a few implementing agencies were desired in order to obtain more detailed information regarding the strategies, objectives, successes, and issues related ramp metering systems in similar metropolitan areas. The following list contains some of the implementing agencies which were considered for the case studies as part of the Minnesota Ramp Metering Evaluation. Seattle, Washington and Phoenix, Arizona were included in the case studies and the results from these interviews are located in Section 12.0. Included within the following list are the potential lessons that can be learned from the agencies, as well as each agency's contact person(s).

1. **Location:** Seattle, Washington
   Agency: Washington Department of Transportation (WSDOT)
   Contact: Mr. Morgan Balogh
   15700 Dayton Avenue North
   P.O. Box 330310
   Seattle, Washington 98133
   (206) 440-4485
   baloghm@wsdot.wa.gov

Potential Lessons:

- Why Seattle's benefits are so substantial compared to Minneapolis-St. Paul's,
- New 'aggressive' model,
- Long history in politically-based decisions,
- Excellent publicity and educational campaigns (keychains to videotapes),
- Updates on the "HERO" program, and
- Effectiveness of the multiple queue detection configuration.

2. **Location:** San Diego, California
   Agency: California Department of Transportation (Caltrans)
   Contact: Ms. Carolyn Rumsey
   (858) 467-3029
   carolyn_rumsey@dot.ca.gov

Potential Lessons:

- Similarities/differences in the strategy adopted (Strategy 2 – Optimize Travel Safety and Efficiency),
- Elimination of HOV bypass lanes,

- Good system and management, and
- Benefits/costs data.

3. **Location:** Phoenix, Arizona
   Agency: Arizona Department of Transportation (ADOT)
   Contact: Mr. Tim Wolfe or Mr. Jim Shea
   2302 W. Durango Street
   Mail Drop PM02
   Phoenix, Arizona 85009
   twolfe@dot.state.az.us
   (602) 712-6622 (office)
   (602) 712-3394 (fax)
   (602) 370-6301 (cellular)
   (602) 662-4630 (pager)

Potential Lessons:

- Ramp metering strategies from a different perspective,
- More laid back management style,
- More 'static' system relative to Seattle or Minneapolis-St. Paul, and
- Why ramp accidents are so high.

4. **Location:** Atlanta, Georgia
   Agency: Georgia Department of Transportation
   Contact: Mr. Joe Stapleton
   #2 Capitol Square, S.W.
   Atlanta, Georgia 30334-1002
   (404) 656-5423

Potential Lessons:

- Ramp metering strategies from a different perspective,
- More laid back management style, and
- More 'static' system relative to Seattle or Minneapolis-St. Paul.

5. **Location:** San Francisco Bay Area, particularly San Jose, California
   Agency: California Department of Transportation (Caltrans) – District 4
   Contact: Ms. Laurie A. Guiness
   1120 N. Street
   Sacramento, California 95814
   (916) 654-6112

Potential Lessons:

- Similar institutional problems as Minneapolis-St. Paul,
- Common technical problems ('issues') with the ramp meters, and
- Benefits/costs data.

12.0 Peer City Interviews

Of the five cities listed in previous section, two cities were selected to be interviewed. The two cities include Seattle (WA) and Phoenix (AZ). They were selected based upon recommendations from the Technical Committee and the Expert Panel. The results of the interviews (9,10) are summarized below.

Seattle, Washington

Seattle started the implementation of ramp meters in 1981, and continues to expand today and into the future. Currently, the Seattle metropolitan area has 105 metered ramps, serving approximately 8,000 lane-miles of freeway. Approximately 85 ramps (80 percent) have HOV-bypass lanes and 20 ramps (20 percent) have dual metered lanes. The average length of the ramps is approximately 750 feet, ranging from 500 to 1,200 feet. The meters are centrally controlled, and normally activated during the weekday a.m. and p.m. peak periods (6:30 to 9:00 a.m. and 3:00 to 6:30 p.m.), but few exceptions exist.

Recently, Seattle implemented a new metering algorithm that "adjusts the meters … based on neural network programming." Washington Department of Transportation (WSDOT) claims it to be more responsive, an improvement over previously used algorithms.

According to WSDOT, the objective of Seattle's ramp metering program is to "improve safety and efficiency" (Strategy 2). This alludes to the conclusion that Seattle has the same strategy as Minneapolis-St. Paul. However, based on further comparative analysis between the two cities, Seattle is less stringent with its metering strategy, and probably should not be considered as adopting Strategy 2. In fact, Lomax and Schrank (2) believe that Seattle's strategy falls between Strategy 2 and 3 (Basic Freeway Management).

WSDOT considers its ramp meter program in Seattle to be very successful, largely due to coupling this program with a solid HOV program. Integration between metering, mainline HOV and HOV-bypass lanes is done as often possible. Furthermore, a substantial amount of time and effort is always invested into working with the communities near a metering system prior to activation. This way, public support has always been excellent, while violation rates remain very low (less than two percent).

Queue lengths are found to be the main constraints to the program. While the ramp metering strategies are area-wide, further refinements are performed at the corridor and community level, to address the constraints. Again, good local community relations are necessary to achieve mutual goals between the agency and the citizens.

When news of the Minnesota Ramp Meter Evaluation project reached Seattle's legislature and local media, skepticism regarding the usefulness of the metering program started to re-appear, something which has not occurred in recent years. WSDOT took this opportunity to re-educate the public about the benefits of ramp metering, and the questions "quickly ended."

Currently, Seattle undergoes collision avoidance studies at the freeway merging areas. Since accident reduction studies typically look at crashes that had occurred, collision avoidance studies analyze reductions in "near misses" or almost-accidents. Generally, ramp meters reduce the potential conflicts at the merging areas by about 30 to 60 percent.

Phoenix, Arizona

The Arizona Department of Transportation (ADOT) started to implement stand-alone ramp meters in Phoenix during the mid-1980s, but did not implement any ramp meter systems (series of meters along a given corridor) until 1995. Currently, the Phoenix metropolitan area operates 121 ramp meters, of which 22 ramps (18 percent) have HOV-bypass lanes and 21 ramps (18 percent) have dual lanes. Ramp lengths vary greatly between ramps, all ranging between 500 feet (older ramps) to 1,300 feet (newer ramps).

The majority of the ramp meters are centrally controlled and capable of adapting to traffic patterns, but operated under fixed-time control. The fixed-time delays range between 3.5 to 15 seconds, which is about the maximum threshold for ramp delay per vehicle. ADOT believes that delays beyond 15 seconds per vehicle would increase violation rates.

Most ramp meters in Phoenix are activated during the a.m. and p.m. peak periods (6:00 a.m. to 9:00 a.m. and 4:00 to 7:00 p.m.), except at ramps near freeway construction zones, where meters are turned on 24 hours per day.

ADOT's main objective for the ramp meter program in Phoenix is to improve the current Freeway Management System, and to "break up platoons." ADOT believes that its ramp meter program has been a tremendous success in Phoenix, especially because of the city's grid system (one square-mile grids throughout the metro area). Unlike Minneapolis-St. Paul, where often geographical constraints such as rivers and lakes force commuters to get on the freeway, Phoenix's grid system provides alternative routes for the short-trip commuters, especially during peak periods. Furthermore, since the grid system is in place in both the downtown and suburban areas, no multiple strategies need to be adopted in Phoenix.

Like Seattle, queue lengths are found to be the constraints of the program. In the past, queue detectors were placed to detect when and how far queues have extended at (or beyond) the ramps. However, continuous adjustments (week-to-week or month-to-month) and balancing between the city street and freeway volumes have proven to be more effective methods in preventing extended backups. Two full-time technicians have been allocated to manage and maintain all ramp meters in the Phoenix metropolitan area.

There has been little or no public involvement both prior to and after the implementation of ramp metering. Still, public and media perceptions are generally positive. According to ADOT, the number of complaints and praises received regarding ramp meters are almost equal one to another.

ADOT raised an interesting issue with respect to their metered ramps with HOV-bypass lanes. Since these ramps have dual lanes (one for all vehicles, the other for HOV or transit only), dual left-turn lanes are often placed on the arterials leading to the ramps. But during the heaviest periods, backups sometimes reach the end of the ramps, even extending towards the left-turn lanes and beyond. The HOV-bypass lanes carry less traffic than their counterparts, leading the regular lane to become very congested while the HOV-bypass lane remains empty. Out of frustration, motorists are found to switch over to the empty left-turn lane and use the HOV-bypass lane illegally. In Phoenix, this situation results in a violation rate of over 45 percent. Under normal circumstances, the ramp meter violation rate is approximately 10 percent. Because of this, ADOT is starting to favor operating dual lane ramp meters over a metered lane with an HOV-bypass lane.

Recently, ADOT passed the legislative effort in raising the amount of fines that can be levied against violators, up to $619. The large sum caused uproar among the citizens and in the local media, but early results show that violation rates have decreased substantially.

As much as possible, ADOT prefers to expand its ramp metering system in Phoenix in conjunction with other freeway management or construction projects. Every system addition requires strong relationships with local city agencies and governments. But so far, there are no political controversies caused by ramp meters.

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