Managed Lanes and Ramp Metering Manual

Part 2: Implementation Plan

Prepared for:

Nevada Department of Transportation

December 2013

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Part 2: Implementation Plan presents guidance on how to implement managed lanes and ramp meters in an effective and consistent fashion throughout Nevada. Relevant background information and definitions are addressed in *Part 1: Introduction and Policies.*

1.0. MANAGED LANES

1.1. Prerequisite Conditions

The following prerequisite conditions must exist for managed lanes to be considered viable.

- **Congestion.** Recurring traffic congestion within a corridor or region during the defined peak periods.
- **Limited resources.** A backlog of unmet travel demand and lack of available resources (e.g., right-of-way, funding, regional consensus, or environmental issues) to address capacity deficiencies by more conventional means such as roadway widening.
- **Lack of trip reliability.** Inconsistent travel times within a corridor or region during the defined peak periods.
- **Public and political acceptance.** Interest by agency stakeholders to pursue options that restrict parts of a freeway for select users groups, in order to provide users a choice for avoiding congestion.

Managed lanes are a congestion management strategy. Congestion occurs when average mainline speeds drop below 35 miles per hour (mph) for several hours during peak periods. This must consistently occur for a managed lane facility to be beneficial to corridor users. If added capacity improvements are programmed to eliminate congestion in the future, then there is no incentive to proactively manage specific lanes on a freeway. Conversely, not managing some lanes eliminates a travel alternative to corridor users, and precludes the potential to preserve some level of mobility to users as demand grows and congestion returns in a corridor.

Two common reasons why many metropolitan areas adopt managed lanes into their long-range plans are the inability to meet demand through conventional roadway widening and/or not having adequate funds to make the needed roadway capacity improvements. Each issue responds to a different set of corridor policy objectives and outcomes. If the corridor cannot be sufficiently widened to meet demand, then preserving some (or all) of the added capacity or some of the existing capacity for managed lanes would potentially meet a mobility goal that might otherwise not be attainable. If funding constraints limit the ability to add capacity, then capacity could be added as a priced managed lane to generate revenue for its funding. Of note, attempting to satisfy multiple goals could put one goal in conflict with the other. For example, promoting carpools and transit could consume capacity in an added lane. This would leave little to be sold for revenue generation. However, if revenue generation is prioritized, then fewer vehicles would be offered free access to the managed lane, which in turn would not promote ridesharing.

Other corridor conditions that promote the application of managed lanes include:

- Relatively long distance trips because managed lanes are typically oriented to the left side,
- Sufficient demand for priority user groups, and

- The ability to load and unload the managed lanes without significantly impacting the general-purpose lanes.

Evidence suggests that the effective overall capacity of a freeway is not always enhanced by converting general-purpose lanes to managed lanes. However, it does offer an alternative to congested travel, all of which is expanded upon in the following sections.

1.2. Operational Options for Managed Lanes

The three operational options that could be used with managed lanes are:

- Concurrent-flow,
- Reversible-flow, and
- Contraflow.

Each option could be applied under any type of managed lane facility (e.g., High-Occupancy Vehicle [HOV], High-Occupancy Toll [HOT], and Express Toll Lanes [ETLs]).

1.2.1. Concurrent-Flow Lanes

Concurrent-flow (or with flow of traffic) operation involves dedicating at least one managed lane in each direction of travel (Figure 1-1). Concurrent-flow lanes operate either 24 hours a day or during certain portions of a day, reverting to general use during off-peak periods (see Section 1.7).

Figure 1-1: A Concurrent-Flow HOV Lane

Concurrent-flow lanes are typically oriented next to the center median to serve high-volume and high-speed traffic. Outside "shoulder" bus lanes could be provided where both ramp volumes and bus volumes are low, thus eliminating any cross-over friction. Most concurrent-flow lanes carry traffic volumes that preclude right-side orientation for safety reasons.

The three types of separation treatment options for concurrent-flow lanes are:

- Buffer separation,
- Barrier separation (i.e., concrete barriers or delineators), and
- Contiguous (i.e., no buffer or barrier separation).

For implementation, the type of separation treatment is to be either barrier separated or contiguous. Buffer separation is not a recommended option. Barrier separation provides an effective and controlled environment that potentially improves operational performance, enforcement, and safety. However, barrier separation often requires more right-of-way, which increases project costs because separate breakdown shoulders are needed for both traffic streams. Access is also more restrictive with barrier-separated lanes. Delineators could reduce initial project capital costs, but this option would increase maintenance costs because delineators are more likely to be damaged and need replacement.

Concurrent-flow lanes are considered for the following conditions.

- A corridor has a fairly balanced peak-period directional split.
- Congestion exists in both directions.
- Design presents this option as the most cost effective from a capital, operational, and maintenance perspective.

Advantages to concurrent-flow operation are as follows.

- The need for directional traffic control features is eliminated.
- There is an opportunity for vehicles to have continuous use of the managed lanes.
- Fewer infrastructure modifications are needed that provide service in one or both directions for relatively the same construction investment.
- It requires less right-of-way (if the lanes are contiguous).

Disadvantages to concurrent-flow operation are as follows.

- There is a greater likelihood that incidents on either the managed or general-purpose lanes will affect both traffic streams (if the lanes are contiguous).
- There are challenges to enforcing lane violations because traffic enters and exits the lanes indiscriminately (unless the lanes are barrier separated).
- There are potential safety issues because of speed differences between the managed and general-purpose lanes (unless the lanes are barrier separated).
- There are fewer access points for incident response (if the lanes are barrier separated).

1.2.1.1. Limited Access versus Continuous Access

Access along a concurrent-flow lane could be allowed at any point (i.e., continuous access) or be restricted to discrete locations (i.e., limited access).[1] Both access types are viable alternatives when planning managed lanes. The most appropriate use is to be based on site-specific conditions and the following guidelines.[2]

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[1] A recent study evaluated HOV lanes in California and concluded that there are no safety advantages between limited-access and continuous-access facilities (Jang 2009). Additionally, there is no proof of significant operational performance differences between the two options.

[2] These guidelines have been adapted from the California Department of Transportation.

A continuous-access facility:

- Typically results in lower costs for analysis, design, construction, operation, and maintenance;
- Requires less engineering resources to make adjustments;
- Could lead to reduced speeds on the freeway because users must focus on vehicles entering and exiting at any point;
- Permits last-minute lane changes to reach exit ramps;
- Reduces concentrated weaving because lane changes occur along the entire corridor as gaps become available;
- Promotes less complex decision making by drivers;
- Is easily utilized during off-peak periods for part-time facilities;
- Requires less separation to accommodate lane closure activities in the managed lane or for the adjacent general-purpose lanes;
- Allows drivers to leave the managed lane easily when there are incidents;
- Promotes a greater investment in enforcement activity and systems to produce violation rates expected with limited-access facilities;
- Would lead to potentially higher occupancy and toll evasion violations; and
- Increases the cost of toll collection because of the need for additional toll readers.

A limited-access facility:

- Requires operational analysis and an iterative design process to ensure the best placement of access points;
- Could necessitate more right-of-way to accommodate access openings;
- Requires additional pavement markings and overhead signing;
- Could lead to congestion across all lanes of traffic because access points could become an initial source of unstable flow and queuing in the managed lane;
- Would potentially impact traffic movement because of more concentrated weaving at access openings and consecutive lane changing across all freeway lanes;
- Could induce violation of the access restriction as users would be unable to access the managed lane when the need is greatest;
- Offers opportunity to restrict lane changing where demand has produced or could produce an operational performance deficiency;
- Accommodates longer-distance trips by discouraging short term use of the managed lanes;
- Could help alleviate bottlenecks where short distance trips cause a lane to exceed its capacity;

- Offers opportunity to ensure that all freeway lanes do not become overloaded regardless of the level of demand they generate;
- Promotes a more orderly flow of traffic when access constitutes a large percentage of total users;
- Requires greater separation to accommodate lane closure activities in the managed lane or in the adjacent general-purpose lanes;
- Limits the convenience of access to some right-side ramps;
- Potentially lowers occupancy and toll evasion violation; and
- Simplifies toll collection because of the need for fewer toll readers.

1.2.2. Reversible-Flow Lanes

Reversible-flow operation is used when there is a substantially higher demand traveling in one direction than the other. This is often based on heavy travel demand altering between the morning and afternoon peak periods (Figure 1-2). The directional split could depend on the number of available general-purpose lanes and dispersion characteristics of commuters. Often times, unequal directional splits exist in urban areas where most of the residents who live in the outlying suburbs commute to their places of employment during the morning peak period and then return home during the evening peak period.

Because of the need to safely separate oncoming freeway traffic and avoid confusion, reversible-flow lanes are always barrier-separated, gated, and controlled through a combination of remote and on-site monitoring.

Figure 1-2: A Reversible-Flow HOV Lane

Reversible-flow lanes are considered for the following conditions.

- Corridors have high peak-period directional splits.[3]
- Substantial congestion exists in the peak direction, and a tolerable (or low) level of congestion exists in the off-peak direction during the respective peak periods.

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[3] This is defined as a more than 60/40 percent split.

Advantages to reversible-flow operation are as follows.

- Less right-of-way is required than for concurrent-flow operation.
- The peak direction is better served where congestion warrants a dedicated lane treatment.
- It allows for easier enforcement because of limited access points.

Disadvantages to reversible-flow operation are as follows.

- It may have higher costs compared to other options because widening could require replacement of median-oriented bridge columns, signs, and drainage structures.
- There is potential for wrong way movements.
- There is a greater need to monitor and quickly respond to incidents.
- There is a longer incident response time due to infrequent access openings.
- It is a challenge to sign and mark the corridor.
- On-site personnel are needed to confirm proper deployment and closure, even if the traffic controls are automated.
- Enforcement vehicles take longer time to return to position following a stop because of infrequent access openings.

1.2.3. Contraflow Lanes

Contraflow operation requires a select set of conditions in which demand is strong in a peak direction and unused roadway capacity exists in the off-peak direction. To accommodate contraflow operation, one or more off-peak lanes are borrowed for peak direction use through the daily deployment (placement and removal) of moveable barriers to separate the opposing flow of traffic (Figure 1-3). Contraflow lanes are created only for the specified operating period and are returned to general-purpose lanes at all other times. This approach requires safe places for vehicles to cross over the median at each end of the contraflow section; a convenient location to place and store moveable barriers next to the median; and a commitment to daily operations by a team of trained personnel to move barriers, place barriers, and activate other traffic control devices.

Figure 1-3: A Contraflow Lane Using a Moveable Barrier

Contraflow lanes are considered for the following conditions.

- There is a high directional split.
- The remaining lanes for the off-peak direction of traffic are not adversely affected by the loss of borrowing one or more lanes.
- There is little need for intermediate access.

Advantages to contraflow operation are as follows.

- Relatively low capital costs are needed to add capacity and reduce traffic congestion in corridors where excess off-peak roadway capacity exists.
- It allows for easier enforcement at a single entrance point.

Disadvantages to contraflow operation are as follows.

- There are high operating and maintenance costs.
- There is limited access to the lanes.
- Enforcement vehicles take longer time to return to position following a stop because of infrequent access openings.

1.3. Queue Bypass Lanes

A queue bypass lane is a short-distance, managed lane that is designed for eligible vehicles to circumvent an isolated bottleneck. The bottleneck could be operationally induced by factors such as congestion, a ramp meter, a ferry dock, or a toll plaza. Queue bypass lanes are considered in conjunction with (or separate from) longer-distance, median-lane treatments on the same roadway, and the most common type of queue bypass lane treatments is the HOV bypass lanes at ramp meters.[4]

Queue bypass lanes are considered for the following conditions.

- Congestion is limited to a site-specific location.
- Modest time saving benefits could be provided for a relatively low cost.

Advantages to queue bypass lanes are as follows.

- It is cost effective because only a limited amount of widening is required for a short distance.
- It could be implemented fast because of the modest nature of the improvement.
- It is a “stand-alone” improvement that does not require full implementation of a managed lane and/or supporting facilities in a corridor.

Disadvantages to queue bypass lanes are as follows.

- It is an insufficient means by which to generate a mode shift toward transit or rideshare.

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[4] HOV bypass lanes at ramp meters are discussed in Chapter 2 (Ramp Metering) of this Implementation Plan.

- There are challenges to enforcing lane violations because traffic enters and exits the lanes indiscriminately.
- Merging into and out of the queue bypass lane is difficult at times.

1.4. Access Options (At-Grade versus Direct-Access Ramps)

Access could be provided at-grade or via direct-access ramps. The ensuing section provides a brief definition and an overview of the attributes for each option.

1.4.1. At-Grade Access

For limited-access facilities, the most common form of intermediate access treatment is providing an at-grade, designated opening in the barrier or providing pavement markings that permit vehicles to enter and exit.

1.4.2. Direct-Access Ramps

Specific high-volume movements could necessitate direct access. Direct-access ramps reduce weaving across the general-purpose lanes and promote time savings for managed lane volumes. Such access ramps typically serve both directions. Low-speed access ramps would serve local streets and transit facilities. High-speed ramps serve major interchanges where one managed lane accesses another. There are two types of direct-access ramps: direct-access local drop ramps and direct-access flyover ramps (i.e., direct connectors).

1.4.2.1. Direct-Access Local Drop Ramps

Local access treatments to major streets and transit facilities (e.g., park-and-ride lots and transit centers) are facilitated through direct-access local drop ramps (Figure 1-4 and Figure 1-5). These ramps allow access to transit facilities when bus volumes warrant. Usually such volumes are equivalent in person movement to person movement provided through regular ramps.

Figure 1-4: Two-Way Direct-Access Local Drop Ramps

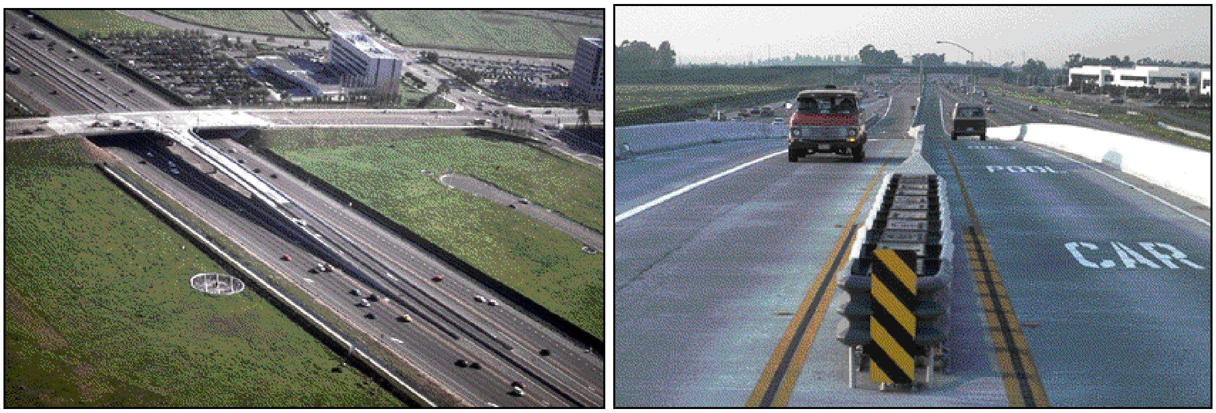

Figure 1-5: Reversible Direct-Access Local Drop Ramps

1.4.2.2. *Direct-Access Flyover Ramps (Direct Connectors)*

In locations where high managed lane volumes are anticipated for connecting traffic between two freeway facilities or with major transit or activity centers, high-speed, direct-access flyover ramps are recommended (Figure 1-6).

Figure 1-6: Direct Connectors

1.4.3. Summary of Access Options

Based on these definitions, Table 1-1 presents a summary of the attributes for each access option.

Table 1-1: Summary of Access Options

Access Type	Attributes
At-Grade Access	♦ Low cost and can be easily modified (relocated or removed). ♦ Most compatible with restricted envelopes. ♦ Requires limited widening (except possibly when a parallel weave lane is needed). ♦ High-volume conditions could increase conflict points and could disrupt the adjacent general-purpose or managed lane level of service (LOS). ♦ Location is critical. If the access is too close to nearby interchanges, weaving conflicts across the freeway could increase.
Direct-Access Local Drop Ramp with a Street	♦ An effective way of collecting and distributing users. ♦ Provides opportunities to control or enforce entering volumes. ♦ Works for reversible-flow or two-way configurations. ♦ Best if not considered at an existing interchange.
Direct-Access Local Drop Ramp to a Park-and-Ride Lot or Transit Center	♦ An effective way to extend an HOV facility into an off-line support facility, which increases travel time savings. ♦ Not recommended for serving other HOVs that have no affinity for the support facility. ♦ Requires circulation consideration within the support facility. ♦ Generally requires high transit and/or rideshare volumes to be cost effective. ♦ Works best for two-way operations, although it is workable for reversible-flow, if drop ramp movements are reversed as well.
Direct-Access Flyover Ramp	♦ Intended for high volumes of managed lane users. ♦ Serves all managed lane users effectively. ♦ Applicable as an intermediate access or termination treatment. ♦ Potentially cost-prohibitive as a means of accessing support facilities. ♦ The least flexible treatment. ♦ Equally appropriate for two-way or reversible-flow operations.

1.5. Planning and Evaluation Process

Planning for and evaluation of managed lanes occurs at different levels. Projects move through regional, corridor, and project levels to final design, construction, operations, and performance measurement.

A broad regional effort is often the initial level of the process. This level focuses on the general needs, issues, and opportunities throughout a metropolitan area. The outcome of this level is a long-range plan that identifies the general types of facilities anticipated for major travel corridors. At times, a regional plan is developed at the onset of compiling a regional vision, and as such, regional plans do not usually define the exact type of treatment or design.

At the corridor and project level, the process is more detailed and focuses on alternative design treatments, access options, vehicle eligibility, and pricing. At the corridor level, different alternatives are analyzed to identify projects to be constructed. The project level is the most detailed of the three levels and is where projects identified at the corridor level are refined. Sections 1.5.2 and 1.5.3 summarize the general approaches to planning and evaluating managed lanes at the regional, corridor, and project levels.[5]

1.5.1. Operating Thresholds

The primary goal of managed lanes is to provide travel time savings and reliability to eligible users. Requirements must be established at an operating level to promote benefits for the largest number of users. This must be determined without creating excessive demand that would lead to congestion. Table 1-2 presents a set of thresholds for different facility types. These thresholds provide general guidance and are dependent on the specific corridor objectives, the type of facility, vehicle eligibility requirements, level of congestion, local conditions, and public perception. A facility's terminus design, ingress/egress locations, and tolling sites also affect the capacity of a managed lane.

Table 1-2: Vehicle Volume Operating Thresholds

Facility Type	*Vehicle Volume Threshold (vehicles/lane/hour)*	
	Minimum	*Maximum*
Concurrent or reversible	700	1,650
Contraflow (borrowed lane in off-peak direction separated by barrier)	700	1,500
Freeway-to-freeway direct connectors	500	1,650
Direct-access local drop ramps* and queue bypass lanes	250	1,400
* Does not apply to ramps used only by buses, such as ramps from a transit center.		

The threshold for the minimum condition is based on the public's perception of how adequately utilized the managed lane appears to be. The number of vehicles using a managed lane on opening day and during the initial phases of the facility must be high enough to justify its restricted use in the eyes of the public. If the public perceives a managed lane to be underutilized during peak periods, pressure could be exerted to reduce or eliminate eligibility requirements. The level of public perception could be specific to the region or maturity of a system. The number of buses within an HOV traffic stream could also affect public acceptance.[6]

1.5.2. Regional Level Planning and Evaluation

As noted, the planning process for managed lanes often begins at the regional level and focuses on the general needs, issues, and opportunities for transportation improvements. Regional

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[5] The American Association of State Highway and Transportation Officials' (AASHTO's) *Guide for High-Occupancy Vehicles* and Federal Highway Administration's (FHWA's) *Priced Managed Lanes Guide* documents further information on planning and evaluation of managed lane facilities.

[6] A facility, once opened to traffic, may have a "ramp-up" period before it achieves the minimum operating threshold.

planning involves input from representatives of the metropolitan planning organization (MPO); transit, federal, and local agencies; and the local communities.

1.5.2.1. Regional Level Screening Criteria

The regional planning process initially entails screening potential improvement options based on a review of existing and forecasted travel conditions compared against baseline and forecasted transportation improvements. The purpose of screening is to determine if specific conditions (including the presence of congestion, travel time benefits, and demand) are present to support a managed lane. The screening process identifies candidate corridors, and tests present and future conditions.

Criteria at the regional planning screening stage tend to be more qualitative in nature, accounting for both the availability of data and the need to examine issues on a macro scale to accommodate variances in corridors and market needs. Criteria for determining the appropriateness of managed lanes typically include the following items.

- **Congestion.** As defined earlier, this major criterion represents the presence of severe and recurring traffic congestion where average corridor speeds drop below 35 mph for several hours during peak periods.
- **Bottlenecks.** Specific traffic bottlenecks or congestion points could cause significant delays. The existence of bottlenecks likely point to the need for some managed lane treatments, such as direct-access ramps to provide a bypass.
- **Travel time savings and trip reliability.** Estimating the potential travel time savings and trip reliability offered by managed lanes is another regional level criterion. General guidance suggests that a managed lane along a freeway or sequence of routes traveled by an average commuter generates at least 5 minutes of travel time savings before a shift starts to occur. A travel time comparison between the managed and general-purpose lanes commonly assumes a 55 mph speed for the managed lane.
- **Transit service.** The level of transit service on a candidate roadway could indicate the need for an HOV lane. Bus volumes could justify some type of HOV lane treatment, particularly at bottlenecks. Factors could include the number of buses, anticipated ridership levels, or bus operating time savings.
- **Travel patterns.** Examining travel patterns (including origins and destinations served by a potential managed lane) is critical to determining the viability of a managed lane facility. The average distance of commuter trips in a corridor often provide a good indicator of viability. Trips need to be long enough on a given route to generate time savings that cause spatial and modal shifts into the managed lane. At this sketch planning level, this analysis usually focuses on travel producers (e.g., residential areas) and attractions (e.g., major employment and activity centers).
- **Managed lane demand.** Existing and estimated levels of carpool/vanpool demand in a corridor often provide information on the potential use of an HOV lane. Vehicle occupancy counts and other available information on eligible vehicles indicate whether enough demand exists to justify a managed lane. Minimum demand is critical to determine facility’s success in its opening year. Person throughput, generated from an assessment of demand, helps to establish if a managed lane will move more people than

an associated general-purpose lane. However, the public's perception of how successful a managed lane is operating is also dependent upon the number of vehicles using the lane.

- **Available space.** Available space should be investigated. A managed lane is incorporated either by widening the affected route or modifying the existing roadway lanes and shoulders to provide for added capacity.
- **Connectivity/Continuity.** A managed lane facility could be enhanced if it is part of a larger system. A specific link in a regional system could affect or be affected by other links. Consideration at the regional screening level to those managed lane segments are critical to an overall network plan. Key links could be needed through interchanges or with major activity centers.

Various tools assist with a screening assessment, including sketch planning tools documented in the American Association of State Highway and Transportation Official's (AASHTO's) *Guide for High-Occupancy Vehicle Facilities* and the *NCHRP Report #414: HOV Systems Manual*, regional travel demand model, and available traffic and transit data. Table 1-3 provides a list of thresholds and tools to use for regional screening criteria.

Table 1-3: Regional Screening Criteria

Criteria	Thresholds to be Met	Input or Tool
Congestion	♦ Corridors that experience average speeds below 35 mph for several hours during each commute period for the opening year and/or planning horizon year.	♦ Speeds and the volume-to-capacity ratios (V/Cs) from available traffic data and the regional model.
Bottlenecks	♦ Locations where speeds fall below 35 mph for several hours during each commute period for the opening year and/or planning horizon year.	♦ Speeds and V/Cs from available traffic data and the regional model.
Travel Time Savings and Trip Reliability	♦ Accrued travel time savings on a given freeway route of 3 minutes minimum per trip. An accrued travel time savings of 5 minutes per trip is desirable between major origins and destinations. ♦ Trip reliability improvement potential.	♦ Output from the regional model.
Transit Service	♦ Minimum number of buses or established ridership for existing and future transit services and plans (based on local policy). Generally, at least six buses/hour are needed to justify a bottleneck bypass or direct-access ramp. ♦ Potential for bus operating time savings.	♦ Transit agency route system and service plan.
Travel Patterns	♦ Average trip distances on freeways are at least 5 miles or more. ♦ Trip affinities exist for specifically-defined employment generators (e.g., there is a minimum of a 20 percent corridor demand exiting to a specific employment generator during the AM peak hour).	♦ Select link analysis from the regional model or from an origin/destination survey.
Managed Lane Demand	♦ Meets minimum demand thresholds illustrated in Table 1-2.	♦ Demand from the regional model. ♦ Sketch planning output based on available occupancy.
Available Space	♦ Opportunity to widen a roadway based on cursory investigations. ♦ Opportunity to modify a roadway through minor changes in geometrics or design exceptions.	♦ As-built roadway plans or programmed plans and studies.
Connectivity / Continuity	♦ Segments critical to an overall network. ♦ Key links through interchanges or with major activity centers. ♦ The candidate managed lane is part of a longer facility.	♦ Demand output from the regional model and select link analysis for identified high volume movements between corridors.

1.5.3. Corridor and Project Level Planning and Evaluation

Corridor and project level planning and evaluation address what type of managed lane would be appropriate and how the facility would be designed, implemented, and operated. To answer these questions, planning efforts involve a greater level of detail. Specific types of managed lane alternatives are to be evaluated, and different operation scenarios are to be considered and compared.

1.5.3.1. Corridor and Project Level Screening Criteria

At the corridor and project level, a more comprehensive analysis is required to review specific site conditions and operations. This in turn requires more field, design, and operational data and input from the affected agencies. Accordingly, criteria are more quantitative and corridor-specific. Demand requires a more detailed level of exploration, which include how much demand is related to transit and van/carpooling, where the demand is coming from (spatial or modal shifts), and how demand impacts other modes or parallel and intercepting corridors. Similarly, congestion, travel time, and trip reliability are examined at a greater level of detail.

Data needs typically involve as-built roadway plans and proposed improvements from various agencies, aerial photographs, land use maps, geographical information systems (GIS) and census information, historical and forecast traffic data (e.g., peak hour, peak period, and daily traffic volumes for ramps and the mainline at various locations), vehicle occupancy data, vehicle classifications, crash incident data, travel time reliability data, and transit and rideshare data. While some data is critical and would need to be collected, most studies rely on available data from a variety of sources.

The following are the corridor and project level criteria that build upon the core criteria found at the regional level.

- **Congestion.** Evaluation of length and duration of traffic queues, weaving, and accident characteristics associated with recurring and non-recurring congestion is required.
- **Travel time savings.** Estimating the potential travel time savings is important when assessing overall effectiveness. Similar to the regional level, general guidance suggests that a managed lane along a freeway or sequence of routes traveled by an average commuter generates at least 5 minutes of travel time savings before a shift starts to occur.
- **Trip reliability.** Trip reliability captures the impact of reducing travel time variability and making travel times more predictable. More predictable travel times allow travelers to better plan their schedules and avoid unexpected delays. Additionally, reliability is critical for transit providers to make their schedules and promoting efficiencies in bus routes. Reliability would potentially reduce bus fleet requirements otherwise needed to service routes. Survey data from priced managed lane facilities suggest that a sizeable percentage of users opt to pay the toll on select days whether they experience a significant time savings or not, to ensure a consistent arrival time. Common measures of trip reliability are 95th percentile travel time (which estimates how bad the delay is on specific routes during the heaviest traffic day) and buffer index (which indicates the amount of extra “buffer” needed to be on time at a destination, 95 percent of the time).
- **Transit services and facilities.** A managed lane facility is meant to support a transit agency’s deployment strategy. Where potential for transit service exists, a market analysis may assist in determining the nature of demand for an express bus or park-and-

ride services. This assessment would define where demand is located, what size facilities would be needed to serve the demand, and what access requirements to an HOV lane would best accommodate the demand once specific alternative sites are identified. Access scheme could affect an agency's ability to utilize the lanes for travel time savings and reliability if the access points limit where a bus exits the freeway to service a transit facility.[7]

- **Managed lane demand.** The basis for selecting a specific managed lane design and operational approach is meeting the intended demand among a wide range of prospective users, including transit buses, carpoolers/vanpoolers, trucks, express users, motorcycles, and low-emission vehicles (LEVs). Each user group exhibits different travel patterns and access needs. Identifying demand for initial and design year scenarios helps establish the appropriate operational strategies. This process assists in confirming that the managed lane is cost effective and appears adequately utilized from the opening year forward. The goal of a demand assessment for overall vehicle and person movement is to prioritize what groups are accommodated over what time periods (with preference extended to ridesharing and transit users). A mix of user groups is to meet the thresholds provided in Section 1.5.1.
- **Access.** Access needs are to be identified, and alternatives are to be evaluated. Access could enhance or adversely affect other roadway operations. In particular, terminal treatments for a managed lane could cause queuing where lane drops occur, even if the condition is eventually eliminated with a full managed lane network build-out. Each condition is to receive careful study (sometimes involving simulation) to arrive at an appropriate balance of roadway needs. This evaluation is critical because travel time savings generated along a managed lane could be lost or could create a net loss in corridor travel time savings to all users, which would outweigh any benefits of the managed lane.[8]
- **Roadway and right-of-way characteristics, constructability, and feasibility.** Practically all managed lanes are oriented to the left to promote long-distance trips and reduce friction with ramps. A roadway's design considers how widening works within the identified right-of-way and environmental constraints, as added lanes might not fit within the remaining available right-of-way. Managed lanes are often implemented as "retrofit" designs into existing and constrained roadways. As such, design tradeoffs (e.g., outer separation, lane, and shoulder widths) are needed. Environmental constraints could also dictate the degree of widening and right-of-way acquisition. Local access features must not encumber existing interchange locations. If the strategy is to convert to a priced managed lane in the future, additional right-of-way and constructability requirements are to be considered to accommodate tolling equipment. An evaluation of these issues often involves a detailed study of the proposed roadway. The level of detail represents up to a 30 percent design where constraints are severe.

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[7] Guides such as NCHRP's *Report 414: HOV Systems Manual* and AASHTO's *Guide for Park and Ride Facilities* can be used to develop sketch planning estimates for park-and-ride demand.

[8] See Section 1.4 of this document and Part 3: Design Manual for all considerations related to access.

- **Environmental issues.** A preliminary assessment of environmental issues could be used as another criterion. One environmental issue particular to priced managed lanes is environmental justice, i.e., whether the managed lane would have a disproportionate impact on low-income users.
- **Cost effectiveness.** The managed lanes are to be assessed in terms of cost effectiveness based on costs, benefits, and impacts. Simplified studies examine only a few variables, such as travel time savings and accident cost savings. More detailed evaluations examine impacts and benefits that involve net travel time saved or lost by different corridor users. These evaluations also analyze emission changes because of managed lane implementation and related performance measures. Individual improvements (e.g., individual ramps) are not subject to a benefit/cost analysis if these improvements are integral to the operations of a specific corridor. Table 1-4 lists suggested components for a benefit/cost analysis and AASHTO's *User and Non-User Benefit Analysis for Highways* (Redbook) provides guidance on completing a comprehensive benefit/cost analysis.

Table 1-4: Components of a Benefit/Cost Analysis

Benefit Components	***Value***	***Comments***
Reduced delay	$/hour	Any reduction in total freeway delay (travel time) could be converted to a benefit by applying a dollar value to a person's time.
Reduced fuel consumption	$/gallon	Fuel saved because of mode shifts is a benefit.
Reduced bus operating cost savings	$/hour	Higher speeds in an HOV lane means that fewer bus hours or buses are needed to provide the required service.
Accident cost savings	$/accident	Any reduction in accidents could be converted to a benefit by applying a dollar value to accident costs.
Vehicle emissions cost savings	$/trip	A by-product of reduced fuel consumption is the reduction in pollutants emitted.
Cost Components	***Value***	***Comments***
Initial capital	$	Cost includes planning, designing, and constructing the HOV lane and is to be annualized as a function of the project's life.
Daily operation	$/year	Depending on the type of facility, costs could include deployment, enforcement, incident response, toll collection, and toll facility maintenance. Notably, toll revenue would decrease daily operation cost.
Maintenance	$/year	Additional maintenance would be needed for a managed lane facility.

- **Financial viability.** An early assessment supports a determination if pricing is needed as a management tool only or whether the revenue generated from the managed lane facility is an important component of funding the facility. An evaluation of travel conditions, congestion, and whether the facility offers a significantly different alternative from the general-purpose lanes would determine how much revenue is required and how much revenue is possible under different eligibility scenarios. Arriving at these determinations could influence a policy shift toward promoting rideshare, how the project is staged over time to maximize benefits, and how much revenue is likely to be generated.

- **Ease of enforcement.** Every design and operational concept generates a different set of enforcement issues that must be addressed during the corridor planning stage with affected law enforcement agencies. For this reason, enforcement agencies are to be involved in managed lane planning. Specific enforcement needs and potential resolutions ultimately influence the facility's design, access plan, and operation plan. Attempting to provide a fully designed facility achieves the highest likelihood that enforcement is performed efficiently and safely. Law enforcement agencies would help to shape facility design to better conduct enforcement operations. [9]
- **Phasing.** Managed lanes must generate meaningful benefits and be incrementally developed so that added capacity does not diminish the benefits of using the managed lanes. A strategic phasing plan in which managed lanes are added first and general-purpose lanes are added later (as demand grows) could be necessary.
- **Safety/incident management.** A managed lane provides both opportunities and obstacles to incident management. Separating the managed and general-purpose lanes is done by installing concrete barriers, delineators, or no barriers through unique lane striping. The needs of emergency vehicles must be assessed early in the implementation of any managed lane concept.
- **Compatibility with other plans and services.** Other highway and transit plans are important factors to reaching a balance of what role the managed lanes is to embrace. Compatibility rather than competitiveness is desired. Managed lanes are to be evaluated by the extent efficiency is achieved among all plans, benefits are provided to each plan, and impacts created by implementation are identified and addressed.
- **Public and agency acceptance.** Outreach determines if a managed lane project is supported by other agencies or if there is potential for widespread sponsorship. Outreach often involves public forums or presentations of why managed lanes are being considered in order to gauge interest and acceptance. Outreach efforts are to address any equity concerns.
- **Operational impacts.** A variety of site-specific impacts could be identified as critical to a specific corridor or facility. Impacts on operations of the general-purpose lanes, adjacent roadway operations, and/or parallel or intersecting streets and intersections are to be considered. Impacts could be particularly focused on any new direct-access features associated with a managed lane. These would require a focused study to confirm how best to design and operate the facility.
- **Other.** There could be other local criteria that are of concern to agency stakeholders and the public (e.g., land use impacts, environmental or community concerns, safety, or

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[9] See Section 1.10 of this document and Part 3: Design Manual for further details on enforcement.

performance). To be effective and meaningful, added criteria must be measurable and allow for differentiation among a number of alternatives.

Table 1-5 defines the considerations for evaluation and measures of effectiveness (MOEs) for each of the criteria noted above.

Table 1-5: Corridor and Project Evaluation Criteria

Criteria	Evaluation Considerations/MOEs	Input or Tool Used
Congestion	♦ Average speeds, LOS, V/Cs, etc.	♦ Operational analysis.
Travel Time Savings	♦ Time saved per mile by link on the corridor. Mainline links and ramp (connector) links are needed to and from each major attraction.	♦ Output from the regional model or operational analysis.
Trip Reliability	♦ The 95th percentile travel times and buffer index. ♦ Percent of time the corridor or project limits are disrupted by non-recurring delay and amount of delay associated with peak period. Comparison can be qualitative.	♦ Travel times from the regional model or operational analysis. ♦ Review of accident and incident data for affected corridor.
Transit Service and Facilities	♦ Incremental number of new riders and diverted riders able to take advantage of the HOV lanes both for ramps and mainline links. ♦ Estimate of the type of support facilities needed to support transit services, their locations, and approximate size. ♦ Compatible with a transit agency's proposed transit service. ♦ Bus operating time savings potential.	♦ Transit service analysis, park-and-ride surveys, and/or origin-destination information. ♦ Review of current and forecast service plans and budgets.
Managed Lane Demand	♦ Minimum vehicle demand is sufficient to meet potential opening year threshold for candidate corridor and segments based on the selected facility type. See Table 1-2. ♦ Actual and percent increase in person movement efficiency on the total freeway (general-purpose plus managed). ♦ Actual and percent increase in average vehicle occupancy of the total freeway. ♦ Actual and percent increase of carpools/vanpools for the total freeway.	♦ Output from the regional model.
Access	♦ Determination of potential access treatments based on demand estimates. A separate study of access locations and types will occur during project level planning.	♦ Output from the regional model, site evaluations, and simulation modeling.

Criteria	***Evaluation Considerations/MOEs***	***Input or Tool Used***
Roadway and Right-of-Way Characteristics, Constructability, and Feasibility	♦ Evaluation of proposed typical sections and layout impacts. ♦ Likelihood that the project will fit within the available right-of-way. ♦ Identification of mitigation required. ♦ Identification of any constructability and feasibility issues.	♦ Standard corridor evaluation practice involving mapping, engineering, and cost estimating. ♦ Evaluation based on typical sections and conditions from as-built plans. ♦ Preliminary engineering and constructability review.
Environmental Issues	♦ Identification and evaluation of potential environmental issues that could affect selection of the design and operation plan.	♦ Cursory environmental studies.
Cost Effectiveness	♦ Comparison of costs, benefits, and impacts to the no-build condition and other build alternatives, with focus on person moving comparative capacity. ♦ Cost effectiveness index: Cost per user minute of travel time saved.	♦ Cost estimates and benefit/cost analysis.
Financial Viability	♦ Identification of potential and likely funding sources compared to project cost. ♦ If revenue is needed to fund the facility, a comparison of priced versus non-priced lane operation by applying a toll feasibility study based on different eligibility policies is to be made.	♦ Cost estimates, programmed and available funding, and toll feasibility study output.
Ease of Enforcement	♦ Identification of an enforcement plan that addresses specific design and operation. ♦ Enforcement provisions addressed in design and feedback from law enforcement regarding these provisions.	♦ Guidance from Part 3: Design Manual. ♦ Input from law enforcement agency.
Phasing	♦ Identification of a phasing plan and potential travel times generated from this plan. Plan must show initial travel time benefits and meet minimum requirements for peak hour demand.	♦ Traffic forecasts output from the regional model.

Criteria	Evaluation Considerations/MOEs	Input or Tool Used
Safety/Incident Management	♦ Determination of lane separation treatment and design of access points. ♦ Identification of incident management requirements and provisions.	♦ Input from incident management providers, engineering, and operations staff. ♦ Existing incident logs for response and clearance times.
Compatibility with Other Plans and Services	♦ Identification of specific benefits and impacts on other plans and services and potential strategies for any appropriate mitigation of any impacts.	♦ Plans and services review and input from the regional model.
Public and Agency Acceptance	♦ Assessment of public attitudes from a wide variety of stakeholders to a specific design and operation plan based on an understanding of benefits and impacts created by the improvement.	♦ Input from a variety of sources, including agency outreach, stakeholder interviews, attitudinal surveys, etc.
Operational Impacts	♦ V/C, LOS, or related comparison between the build and no-build conditions. This is based on site-specific evaluations.	♦ Input from the traffic operational analysis and simulation modeling at specific locations.

These evaluation considerations have a cumulative impact on how a managed lane is designed and operated. The output from a corridor or project evaluation provides two distinct products: a design plan (Section 1.5.4) and an operation plan (Section 1.5.5).

1.5.4. Design Plan

A specific conceptual design plan builds upon the corridor evaluation through a review of feasible alternatives. This plan is oriented around an evaluation that has used some or most of the criteria discussed above. The plan would likely be corridor specific or applicable to a network of lanes on several corridors. This direction would depend upon the nature of the problem and the demand characteristics. Regional consistency is desirable, and consistency has been achieved after a first or second managed lane facility has operated for some length of time and has been changed or altered to meet local conditions before institutionalizing consistency in its application.

The design typically consists of a scaled roadway layout, typical sections, identified access features, transit support facilities, and cost estimates. A phasing plan is needed if multiple facilities are anticipated to be implemented separately.[10]

1.5.5. Operation Plan

The operation plan consists of a description of how the managed lane facility would operate during the initial year of opening and for future years based on anticipated changed conditions.

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[10] Managed lanes design is addressed in Part 3: Design Manual.

An operation plan is to be established early in the project development process because the specific plan impacts overall facility design. Each component to the operation plan often builds upon existing departmental and agency working relationships and programs in an attempt to integrate facility needs into other congestion management strategies and programs. An operation plan generally includes:

- The responsibilities of the respective agencies;
- How routine management is to be administered;
- Organizational structure for changing rules and regulations;
- Rules and regulations for hours of operation and eligibility;
- Enforcement requirements specific to occupancy enforcement, access infractions, and toll evasion infractions;
- Handling of unique users (e.g., LEVs, motorcycles, emergency vehicles, and deadheading buses);
- Marketing and outreach activities;
- Legislative statutes related to the operation plan;
- Procedures for temporary suspension of rules and regulations because of incidents on the freeway;
- Pricing requirements, including pricing strategy, technology, field application, functional requirements, administration, and maintenance; and
- Performance and monitoring data collection, compilation, and dissemination procedures.

To the extent possible, an operation plan is to be consistent among all facilities in the region and would ideally align with a regional operation plan. Since managed lanes involve proactive and ongoing management, the operation plan is a key tool to promote agency cooperation, coordination, and success in meeting the overall goals and objectives for mobility in the corridor.

1.6. Establishing Eligibility

Restricting a dedicated lane to specific users limits vehicle demand. User restrictions for HOV lanes have taken the form of eligibility requirements based on the requisite minimum number of people traveling in a vehicle. Over the years, restrictions on HOV lanes have evolved to include various occupancy levels (e.g., vehicles with a minimum of two or three occupants) and types of occupancy-exempt vehicles (e.g., motorcycles, LEVs, and emergency vehicles). Restrictions could be in effect 24 hours a day or vary by time of day or day of the week. A managed lane using a variable eligibility strategy could restrict use to vehicles with a minimum of three or more occupants during the peak commute hours, and then relax restrictions to include lower occupancy vehicles and occupancy-exempt vehicles or other users during off-peak periods.

1.6.1. Occupancy

A vast majority of HOV lanes are restricted based on minimum occupancy requirements to two or more persons (HOV 2+) per vehicle. An HOV 2+ eligibility policy engages the widest rideshare market to be served partly because less effort is involved in forming a carpool. If HOV 2+ demand grows beyond the managed lane’s maximum operation threshold, then various strategies could be applied. These strategies include addressing bottlenecks through lane expansion, raising occupancy requirements during the peak demand periods to HOV 3+, allowing two-occupant vehicles to use the lane through pricing or a permitting process, leveraging access restrictions, or applying other means to regulate demand. If forecasted or observed HOV volumes fall short of the minimum threshold for opening year conditions, then pricing the general traffic for a defined period could be considered.

Setting an HOV 3+ person occupancy requirement provides greater person-moving capacity, poses less risk of an HOV lane reaching its operation threshold, and better ensures a high level of service (LOS) within the HOV lanes. Conversely, fewer vehicles are eligible; it is much harder to attract and sustain HOV 3+ vehicles; and the resulting level of use potentially is a source of local criticism. It is often difficult to generate enough HOV 3+ demand to support a perception of adequate use. This is particularly the case for facilities serving dispersed trip patterns in suburban settings. Where an HOV 3+ restriction has been imposed over an extended period, commuters have reverted to informal "instant carpooling" (“slugging”), where drivers pick up random passengers along their route as a means of meeting occupancy requirements on a day-to-day basis.

Additionally, for program goals and objectives to be achieved, changing user eligibility to HOV 3+ requires a significant behavioral shift on the part of commuters. It is recommended that this change be preceded by an intensive marketing and public/political educational campaign with sufficient time to restructure carpools from HOV 2+ to HOV 3+. The campaign must be sensitive to local public and political acceptance. Support services are to be available to handle those who cannot meet the more restrictive requirements. These services include additional bus services, vanpool seed fleets, and coordination with employers to reinforce alternatives to single-occupant auto use.

1.6.1.1. HOV to HOT Lane Conversion

The following situations could necessitate the conversion of HOV lanes to HOT lanes.

- **An HOV 2+ or 3+ facility is underutilized.** If an HOV 2+ managed lane is not meeting the minimum volume thresholds illustrated in Table 1-2, single-occupant vehicles (SOVs) are granted access by paying a toll. Similarly, HOV 2+ vehicles are allowed access by paying a toll if the HOV 3+ facility is underutilized.
- **When an HOV 2+ facility is congested.** In this case, typical mitigation is to increase occupancy requirement from HOV 2+ to HOV 3+ and revoke LEV exemptions if they were originally allowed. These changes, however, would potentially reduce the HOV lane demand. The newly opened capacity is utilized by converting the facility to a HOT lane, so that those SOVs willing to pay a toll fill the excess capacity.
- **When a facility operates at capacity during the peak period but has excess capacity during other periods, especially during the fringes of the peak periods.** If the general-purpose lanes are still congested during non-peak periods, the managed lanes operate as an HOV-only facility during peak hours and a HOT-lane facility during other time periods.

Challenges with HOV to HOT lane conversion involve determining locations for toll collection equipment and installation, and signage modifications.

Federal law (23 United Stated Code [USC] 166) sets requirements for HOT lane conversions. Under this law, the most important conversion requirement is not degrading the facility after conversion.[11] The most recent iteration of 23 USC 166 is to be reviewed and conformed if NDOT considers HOT lane implementation in the future.

1.6.2. Vehicle Type Eligibility

The following is a list of vehicle type eligibility requirements.[12]

- **Motorcycles.** Consistent with 23 USC 166, motorcycles are allowed in HOV lanes unless a safety study determines otherwise.
- **LEVs and energy-efficient vehicles.** Nevada Revised Statutes (NRS) 484A and 23 USC 166 grants NDOT the authority to allow LEVs and energy-efficient vehicles that meet specific performance requirements (defined in USC166 (f) (3)) access to an HOV lane. For HOT lanes, LEVs and other energy-efficient vehicles could be charged a reduced toll compared to other vehicles. If LEVs are considered, then a safety and impact study is required to assess whether these vehicles could be accommodated. Any inclusion of LEVs and energy-efficient vehicles is subject to annual review by NDOT. Per 23 USC 166, if the presence of these vehicles cause the managed lane to become degraded, then the vehicles are no longer eligible to access the facility. Determining that LEVs and energy-efficient vehicles are ineligible requires advance notification to these users prior to terminating preferential privileges.
- **Trucks.** Trucks with more than two axles and vehicles towing trailers are not allowed in HOV lanes because of adverse impacts on speeds, reliability, and safety; and is not consistent with the HOV goal of moving people. However, HOV lane design must account for trucks use because HOV lanes could be converted in the future to other types of managed lanes that would allow trucks.
- **Emergency vehicles.** Emergency vehicles responding to an incident are allowed in managed lanes.
- **Dead-heading transit.** Dead-heading public transit buses are allowed in managed lanes.

1.7. Establishing Hours of Operation

Managed lanes either operate full time (i.e., 24 hours a day) or part time (peak-period only or extended peak period). There are advantages to each approach, and on a national level, about half of all managed lanes operate full time with the other half accommodating general-purpose operations when not needed.

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[11] Per 23 USC 166, a facility is considered degraded if vehicles operating on the facility are failing to maintain a minimum average operating speed of 45 mph 90 percent of the time over a consecutive 180 days during morning or evening weekday peak hour periods or both.

[12] Federal laws (specifically 23 USC 166), State laws (specifically NRS 484A.460 and 463), and the most recent version of *Federal-Aid Highway Program Guidance on High-Occupancy Vehicle Lanes* (2008 at the writing of this document) are to be consulted on any concept and issue related to eligibility.

Whichever approach is applied, operational periods are to be regionally consistent. The prevailing policy must be understood by users and communicated on signs, pavement markings, and other traffic control devices. If the managed lane is open to all traffic, then how the managed lane is differentiated or physically separated could cause confusion outside the operating period. Even if a managed lane facility is operated on a 24-hour basis, communication for the traveling public is critical because surrounding states could have facilities that operate only part time. The following describes operating scenarios.

- **Full-Time Operation.** Operating a managed lane facility full time (i.e., 24 hours a day) provides travel time and reliability benefits for users at all times, during recurring and non-recurring congestion. Full-time operation is most commonly used with concurrent-flow lanes. It is easier to sign, mark, and enforce because there are no changes by the time of day. Additionally, full-time operation may promote wider acceptance of the facility. However, the managed lane may appear empty during the off-peak periods. This could lead to "empty lane syndrome" where traffic in the general-purpose lanes flow freely and there is no advantage for any traffic to use the managed lanes.
- **Extended Peak-Period Operation.** Under this scenario, the operation period is extended for a major portion, but not all, of the day. Potential limitations of extended hours include motorist confusion, which complicates enforcement, and the need for additional signing, which preferably is dynamic in nature. Extended operating hours are commonly found on reversible lanes and on facilities where demand around special events exist.
- **Peak-Period-Only Operation.** This operation scenario targets the periods of congestion when demand for a managed lane is the greatest. This scenario converts the managed lane to general-purpose use during off-peak periods. Peak-period-only operations typically reserve a two to three-hour operating period in the AM and PM peak periods. Lane violations are commonly greatest in the transition periods when restrictions take effect. Peak-period-only operation becomes complicated if pricing is employed because the rules are more difficult to communicate to motorists.

For concurrent-flow lanes, both full-time and part-time operations are to be evaluated in the regional managed lanes plan. Law enforcement, design, and operations staff are to be involved in this evaluation. Reversible or contraflow lanes are to have defined operation periods dictated by demand during the peak period. By nature of how they operate, reversible and contraflow lanes are to only be operational during the affected period.

1.8. Performance Measurement

Measuring performance of managed lane operations is conducted for a variety of reasons. Before and after studies are conducted to determine whether the anticipated benefits outlined for the region and corridor's goals and objectives are being met. Ongoing monitoring and periodic evaluations ensure that the project is providing the desired results and, more importantly, is helping to validate changes or enhancements in design or operational policies. Information on vehicle volumes, travel times, occupancy trends, transit patronage, violation rates, and crash data are critical to an efficient and operationally-sound project.

The steps for measuring performance are presented in the following order.

- **Step 1.** Define the overarching goals. What broad-based objectives are hoped to be achieved?

- **Step 2.** Select performance measures that are associated with the established goals. Which measures appropriately capture the goals?
- **Step 3.** Locate data elements that support the generation of the performance measures. It is important to identify whether these elements are available prior to entering the "before" results period.
- **Step 4.** Determine how other concurrent projects and transit modifications affect the ability to alter the measured project between the before and after periods.
- **Step 5.** Identify one or more control groups to determine how regional factors contribute to traffic changes on the measured project.

As described above, performance measurement commences with setting performance measures that directly correlate with goals and objectives. Table 1-6 provides example measures that mirror common goals and objectives for managed lanes. Target thresholds for each performance measure are to be identified to establish whether the managed lane has met the specified objective.

1.8.1. Data Needs

Data for the performance measures are typically available from local or regional modeling, traffic data, and other members of the team involved in implementation and operation of the managed lane facility. Data is to be collected in advance of facility opening to allow for a before and after evaluation comparison. Obtaining data for 2 to 3 years alongside the general-purpose lanes (preferably prior to any construction activities) helps to form a trend analysis. The basic information needed for such studies includes:

- Vehicle counts for general-purpose and dedicated lanes,
- Occupancy counts,
- Travel time and speed information for general-purpose and managed lanes,
- Safety and crash data,
- Violation and enforcement data, and
- Survey information to gauge attitudes and preferences from users and non-users.

1.8.2. Agency Roles

Each stakeholder agency plays a role in monitoring the performance of a managed lane facility. NDOT, the MPOs, law enforcement, and local agencies all have unique needs and ways to access the required data. NDOT is generally responsible for traffic data and relies on transit providers for transit information. Occupancy data generally demands dedicated, periodic field counts that are more reliable and easier to obtain than regional occupancy data. Law enforcement would provide lane violation information. Attitudinal survey data is a dedicated effort that is conducted through NDOT or other local agencies.

Table 1-6: Sample Performance Measures

Goals and Objectives	*Performance Measures*
Improve the capability of moving more people	♦ Actual and percent increase in person movement. ♦ Actual and percent increase in average vehicle occupancy rate. ♦ Actual and percent increase in carpools and vanpools. ♦ Actual and percent increase in bus riders.
Provide travel time savings and a more reliable trip	♦ Comparison of the peak period and peak direction travel time in the managed lanes to adjacent general-purpose lanes. ♦ Increase in travel-time reliability for vehicles using the managed lanes.
Increase 'per lane' vehicle volume of the freeway	♦ Change in the peak hour "per lane" vehicle volume for all lanes.
Increase safety and performance of transit service on the corridor	♦ Improvements in vehicle productivity (operating cost per vehicle-mile, operating cost per passenger, operating cost per passenger-mile). ♦ Improved bus schedule performance on portions of routes using the HOV lane (on-time performance). ♦ Crash rates for affected bus trips (before and after).
Not adversely impact safety	♦ Number and severity of crashes for the managed lanes versus the general-purpose lanes. ♦ Crash rate per million person-miles of travel. ♦ Crash rate per million vehicle-miles of travel (VMT).
Enhance impacts on air quality and energy consumption	♦ Number and reduction in emissions (amount per passenger). ♦ Number and reduction in total fuel consumption (amount per passenger). ♦ Number and reduction in growth of VMT and vehicle hours of delay (VHD).
Be a cost effective improvement	♦ Benefit/cost ratio. ♦ Benefit per traveler compared to other facility investments.
Generate revenue to cover pricing cost or fund operations and capital invested	♦ Gross revenue generated by tolling the managed lane. ♦ Net revenue generated, excluding operation and administration. ♦ Toll leakage (violators that do not pay).
Have public support	♦ Support for the managed lane among users, non-users, the general public, and policy makers. ♦ Violation rates (percent of vehicles not meeting occupancy requirements).

Source: Adapted from AASHTO's *Guide for High-Occupancy Vehicle Facilities*.

1.8.3. Performance Measures

Table 1-7 depicts performance measures under each managed lane goal defined in Part 1: Policy Manual.

Table 1-7: Performance Measures

Managed Lane Goal	Performance Measures	Threshold
Goal 1: Optimize the movement of people	♦ Number of person throughput in the managed and general-purpose lanes.	♦ More person movement in the managed lane than an adjacent general-purpose lane.
	♦ Average vehicle occupancy rate within corridor.	♦ Higher than “before” condition.
	♦ Number of carpools and vanpools within corridor.	♦ Higher than “before” condition.
	♦ Number of bus riders on affected routes and services.	♦ Higher than “before” condition.
Goal 2: Provide incentives to share the ride	♦ Peak-period and peak-direction travel time in the managed lane(s) and in adjacent general-purpose lanes.	♦ Faster travel times in the managed lane than adjacent general-purpose lane. ♦ Differential of 30 seconds per mile or greater over the general-purpose lane within 5 years.
	♦ Travel time reliability measures for vehicles using managed lane(s) and adjacent general-purpose lanes.	♦ Lower 95th percentile travel time and buffer index than “before” condition. ♦ Lower 95th percentile travel time and buffer index than adjacent general-purpose lane.
Goal 3: Increase bus transit efficiency	♦ Vehicle productivity (operating cost per vehicle mile, operating cost per passenger, operating cost per passenger-mile).	♦ Better than “before” condition.
	♦ Bus schedule adherence (on-time performance).	♦ Better than “before” condition.

Managed Lane Goal	Performance Measures	Threshold
Goal 4: Not unduly impact existing traffic operations	♦ General-purpose lane volumes.	♦ Equal or lower than “before” condition.
	♦ Total corridor throughput.	♦ Higher than “before” condition.
	♦ Speeds in managed lanes.	♦ Higher than 45 mph.
	♦ Speeds on all lanes.	♦ Better or equal to “before” condition.
	♦ Observed number of incidents and severity of accidents for the managed lane and adjacent general-purpose lane.	♦ Better or equal to “before” condition based on accident experience (minimum 3 years).
	♦ Accident rate per million VMT and per million passenger miles of travel for the managed lane and adjacent general-purpose lane.	♦ Better or equal to “before” condition based on accident experience (minimum 3 years).
Goal 5: Secure public support	♦ Observed support for the facility among users, non-users, general public, and policy makers.	♦ Net positive response (above 50%) based on agency, policy maker, and public feedback.
	♦ Lane violation rates (percent of vehicles in the managed lanes not meeting the occupancy requirement).	♦ Rate of 5% or less during peak commute periods.
Goal 6: Consider congestion pricing as a means to optimize system performance (as opposed to generate revenues)	♦ No quantitative performance measure.	♦ Not applicable.
Goal 7: Promote goods movement by trucking if possible	♦ No quantitative performance measure.	♦ Not applicable.

1.8.4. Reporting

Performance measurement is particularly critical for a region’s first few managed lane facilities. As such, reporting is to be frequent throughout the first year and periodic thereafter. A report on usage, time savings, and modifications in transit and rideshare use after the first six months of facility opening and after one year of operation is recommended. After the first year, frequency is established based on data needs, data availability, performance reporting desired by local partners, and changes in operation conditions that could justify a change in operation policy. For controversial projects, monthly performance updates are likely needed for the first few months.

1.9. Pricing

Pricing (also referred to as priority pricing, variable pricing, value pricing, or congestion pricing) managed lanes is a means to manage traffic demand by altering pricing to encourage or discourage use and to generate revenue to help offset capital and operation costs. Pricing involves charging a fee (or toll) to travel a given distance. The price could vary according to the time of day, the day of week, or the level of congestion on a freeway. Pricing provides motorists with alternatives when traveling in congested corridors.

While pricing has an application in many different contexts, the primary purpose is to manage demand so that the managed lane(s) does not become congested. Higher tolls are usually charged when congestion is heaviest and delay is at its worst. Lower tolls or free access is provided to some or all users during periods of lowest demand. Pricing is applied to better balance demand to lane capacity and encourage some peak period users to shift to lower demand periods.

The following guidelines are to be considered when planning priced managed lanes.

- Develop realistic project objectives and easy-to-understand pricing strategies, particularly for a region's first priced managed lane facility.
- Define the back room administration and operation needs and the agency's roles in handling these needs.
- Develop a policy for allocation of revenues (including excess revenue) in advance. Define an action/policy if revenue does not cover costs.
- Evaluate and understand the impacts of pricing on other high priority users (e.g., transit and rideshare users).
- Identify agency and elected leader champions and gauge public attitudes through surveying.
- Engage the public early and frequently in the planning process.

FHWA's *Priced Managed Lanes Guide* provides further information on pricing.

1.9.1. Price Variability

Price variability refers to the change in price according to a fixed schedule by time of day (i.e., fixed variable pricing) or in real-time by the prevailing traffic conditions (i.e., dynamic pricing). With dynamic pricing, fees are responsive to the operating conditions of the managed lane. Traffic flow rates are monitored and prices are adjusted according to a prescribed plan that assures flow rates are sustained. Depending on the price variability concept, the managed lane facility could involve additional subsystems (e.g., traffic monitoring devices, advance signage, and/or more extensive modification to an existing toll collection operation in order to accomplish the pricing objectives).

1.9.2. Separation Treatments for Pricing

The simplest approach to pricing is to operate a single tolling and enforcement site for the managed lane facility. However, this approach requires that the facility be physically separated so that toll evaders cannot enter or exit at will. In this environment, toll transactions are easier to accommodate, and access violations are eliminated. More complex applications have been implemented in recent years where access is not as restricted (i.e., no barriers) and the number of tolling points is more widespread along a facility. Multiple readers and tolling installations are installed to collect tolls and catch evaders.[13]

1.9.3. Electronic Toll Collection (ETC)

Pricing a managed lane involves electronic toll collection (ETC) through one or several locations along a facility. ETC encompasses the use of various technologies that eliminates the need for customers to stop and make cash transactions at a toll booth. ETC links the vehicle to an account maintained by a host computer system through communications infrastructure.

ETC systems rely on three major in-lane/roadway components.

- **Automatic Vehicle Identification (AVI).** AVI features a radio frequency (RF) device called a transponder (or toll tag), which is located in the vehicle that transmits a unique identification (ID) and other information that is stored in the transponder, to an antenna (Figure 1-7) located on a gantry or in a toll lane. The information is received by a toll reader located in a nearby roadside cabinet.
- **Automatic Vehicle Classification (AVC).** AVC features sensors located at the tolling point that verify a vehicle's classification based on the vehicle's profile and number of axles. The classification of a vehicle is sometimes encoded on the transponder and matched to the classification identity from the sensors.
- **Photo Enforcement Systems.** A photo enforcement system captures images of the license plates for toll evaders via cameras (Figure 1-7). Violations include vehicles without a readable transponder, a vehicle class that does not correspond to a class stored on the transponder, or an invalid account held by the vehicle owner. Automated license plate recognition (ALPR) is the technology used to automate enforcement functions.

Figure 1-7: Cameras and Overhead RF Antenna

There are many observed variations on the typical tolling systems. Integrating this technology can be a complicated process, and frequently administrative agencies hire a system integrator to incorporate the technology to their existing toll environment or to develop a new toll system. It is recommended that the selected transponder technology be compatible with other regional or

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[13] Additional resources (see section references), including FHWA's *Priced Managed Lanes Guide*, provide further information on these new technologies where toll collection and automated enforcement is handled without specifically separating the managed lanes from the general-purpose lanes.

statewide toll road operations so that user interoperability is possible with other facilities. Interoperable systems allow a single ETC account to be accepted at each managed lane facility within the interoperable system.[14]

The key to determining the applicability of any given technology includes operating functions, capital and operating costs (both agency and patron), security, product maturity, compatibility and interoperability with existing or planned systems, standards compliance, maintainability, and ease of use.

1.10. Enforcement Considerations

Enforcement is critical to the successful operation of any managed lane facility. The role of a managed lane enforcement program is to ensure that operating requirements are maintained to protect travel benefits, to discourage unauthorized vehicles, and to maintain a safe operating environment. Visible and effective enforcement promotes fairness and maintains the integrity of the facility.

Enforcement is aided by new technologies that locate toll evaders, but on-site presence would still be needed, particularly for occupancy enforcement. As the facility's operation rules and prices change from peak to off-peak periods or from one day to the next, enforcement becomes more complicated.

Enforcement policies and programs perform a number of important roles. First, policy and program development ensures that every appropriate agency is involved in the process and that all groups have a common understanding of the need for enforcement. Participation is important from lane enforcement agencies, state and local judicial systems, transit agencies, local municipalities, MPOs, federal agencies (e.g., Federal Highway Administration [FHWA] and Federal Transit Administration [FTA]), and other groups throughout the development and implementation of enforcement policies and programs. Second, the information provided to the public, especially travelers in the corridor, helps introduce the managed lanes and communicate the guidelines for how to use them. Third, enforcement policies and programs maintain the integrity of the facility by deterring possible violators, and promote the safe and efficient use of the facility.

Managed lane enforcement is seldom dedicated to a given facility. Law enforcement officers perform a variety of services on the freeway system, and managed lane enforcement often competes with other activities.

Enforcement is either on-site or automated concurrent with ETC.[15]

1.11. Incident Management

A strategy that responds to minor incidents, crashes, and other non-recurring events that disrupt the flow of traffic is called incident management. The goal of incident management for managed lanes is similar to incident management for general-purpose lanes. The intent is to react and clear incidents and other capacity-restricting events in a minimum amount of time to maintain overall

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[14] The websites *http://www.tollinterop.org* and *http://www.ibtta.org* provide resources on interoperability.

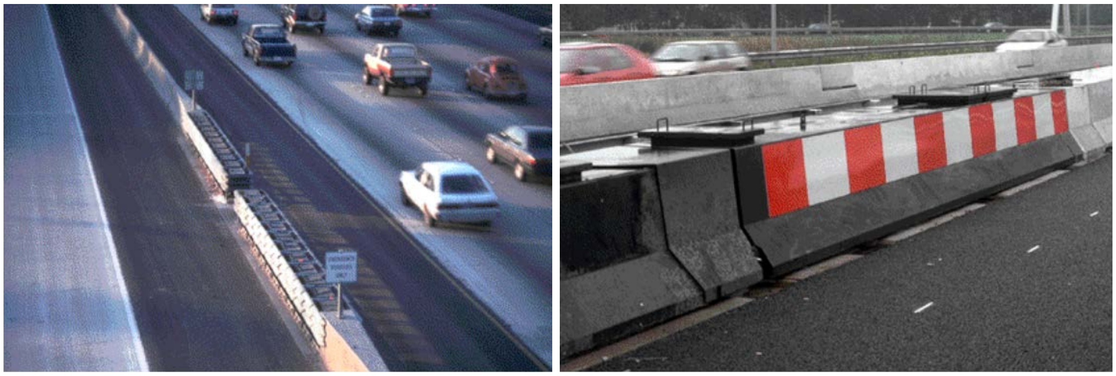
[15] Enforcement area design is addressed in Part 3: Design Manual.

roadway availability with reliable travel times. For priced managed lanes, paying motorists have an increased level of expectation for reliable service that must be addressed as a part of the overall incident management strategy for the highway.

There are four elements involved in incident management.

- **Detecting.** Verifying the type, nature, and location of an incident involves detecting the incident. Detecting the incident comes from witnesses calling in law enforcement on cell phones, radio dispatches from highway patrol, monitoring from a traffic management center (TMC), or roadside or pavement detectors monitoring traffic flow. Confirmation of the incident, the actual location of the incident, its significance, and the required response could be determined using closed-circuit televisions (CCTVs) or newer technologies, such as GPS-based communication.
- **Responding.** Responding to an incident entails various methods to resolve a disruption. Traditional means of removing disabled vehicles generally work for contiguous lanes, but it does not work as well for barrier-separated lanes because of the restricted access roadway setting. A typical response involves the deployment of a tow truck to remove the disabled vehicle. This could require special agreements with local tow truck companies or with local or state agency towing operators. Whenever a major incident disrupts all lanes and when barriers do not preclude traffic from using all lanes, emergency and traffic management personnel could allow traffic into the managed lane for the affected period to help clear the scene. Announcement of this temporary access would occur via radio and/or DMSs. Responsiveness is enhanced for barrier-separated lanes if openings in the barrier or barrier gates are included at periodic intervals (1 to 2 miles) (Figure 1-8). Some facilities (particularly priced managed lanes) have service patrols that regularly patrol the facility during peak periods and assist with incident identification and response.
- **Clearing.** Clearing an incident within a managed lane involves removing the impediments (usually the disabled or damaged vehicles). This would be done using the same methods as used for the general-purpose lanes. A breakdown shoulder adjacent to the managed lane could provide refuge for a disabled vehicle and the means for emergency personnel to quickly access the scene of an accident. Barrier separation could confine incidents in a facility from affecting the general-purpose lanes; however, these separation treatments also inhibit emergency vehicles and tow trucks from accessing the managed lane without the presence of emergency barrier openings.
- **Communication to motorists.** Conveying real-time information to managed lane users requires many communication channels. Best facilitated from a TMC, communication to users is provided in advance of ingress locations, so that if the facility needs to be closed, users could choose other routes. On reversible-flow facilities, communication verifying the direction of operation could double as a means of providing incident management information.

Figure 1-8: Examples of Emergency Barrier Gates



The above four elements have different applications for different types of managed lane facilities. For example, a much more intensive monitoring function is needed for a reversible or contraflow facility where wrong way movements must be quickly detected and intervened to avoid potential crashes. Additionally, the facility is to be closed and verified empty of vehicles (including disabled vehicles) before the reversal process begins. This is done by manual inspection via teams driving the facility or by complete CCTV coverage of the facility. Similarly, a facility that does not contain a full emergency breakdown shoulder (a minimum of 8 feet) is likely to experience a higher rate of failure as minor incidents disrupt traffic flow more when compared to a full design. This type of facility, therefore, demands more monitoring and incident response countermeasures. Specific strategies applied to each setting are unique and often adjusted based on experience.[16]

1.12. Resource Needs

Successful managed lane development and implementation requires a commitment to build, maintain, and operate the managed lanes in perpetuity. Operation requirements are greater for overall freeway operations because demand must be aggressively managed and use must be thoroughly enforced. Enforcement of managed lanes demands both early involvement of respective law enforcement entities and ongoing commitment. Resource needs also involve other agencies that are responsible for transit services and rideshare promotion. These are roles not traditionally included on typical highway projects. Pricing could require a toll administrator to handle the transactions associated with collecting tolls, which in turn necessitates a high degree of customer interaction at the transactional level. This is another role that is not traditionally part of freeway operations. Each of these functions varies widely and depends on available and interested agency partners.

Table 1-8 provides resource needs for the various types of managed lanes.

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[16] FHWA's *Priced Managed Lanes Guide* provides additional information on incident management.

Table 1-8: Resource Needs for Various Managed Lanes

Type of Facility	Resource Need	Evaluation of Resource Need
Barrier separated concurrent-flow lanes	Daily monitoring/incident management.	Closer monitoring needed that allows for diversion of traffic around an incident.
	Enforcement.	Moderate.
	Maintenance of related traffic control devices.	No different than maintaining the adjacent general-purpose lanes.
Contiguous concurrent-flow lanes	Daily monitoring/incident management.	No different than monitoring the adjacent general-purpose lanes.
	Enforcement.	Significant because this type of managed lane is easier to violate.
	Maintenance of related traffic control devices.	No different than maintaining the adjacent general-purpose lanes.
Reversible-flow lanes	Daily monitoring/incident management.	Significant because managed lanes must be reversed before/after each peak period and gates must be opened/closed.
	Enforcement.	Significant increase due to potential wrong way movements.
	Maintenance of related traffic control devices.	A significant increase for redundancy and rapid maintenance responsiveness for safety reasons.

1.12.1. Funding

Funding for managed lanes could be from a match of federal, state, and local highway sources, or from public-private-partnership (PPP) initiatives. Some projects or transit support facilities for managed lanes have been implemented with matching funding from the FTA. NDOT is expected to be the sponsoring agency because the vast majority of managed lanes are likely to be integrated on roadways owned by the State. The process of planning and programming funds is often augmented or shared with a local transportation agency (e.g., an MPO). In such instances, the local agency is responsible for regional transportation planning, programming, and providing input on prioritizing projects for their respective region.

Funding needs for project planning include capital project functions (e.g., planning, design, construction, and administration), costs associated with operations (e.g., enforcement staffing, training, operations management, and monitoring performance of operations), and maintenance needs (e.g., roadway and structures inclusive of specialized traffic control devices or tolling equipment). Estimates of these costs are documented under budget development and capital programming activities. Some costs are related to onetime events, and marketing costs are to be considered for the facility's opening and for ongoing facility activities. Operation and maintenance costs are typically funded by local, State, and federal funds or from toll revenues. Local funding could be supported by transit providers, particularly where there is a significant transit service component associated with operations.

Agencies are to investigate cost effective ways to include managed lane improvements as part of other funded projects. With adequate knowledge of programmed projects, agency resources, and funding sources, many elements of a corridor or regional managed lane facility could be implemented with a minimum investment or with an investment targeted to specific projects that are strategic to the effectiveness of an overall plan.

Managed lane costs vary depending on the type of facility, separation treatments, access treatments, available right-of-way, and infrastructure to be re-constructed. All projects involve roadway widening or restriping to maximize available pavement use. Restripe treatments generally cost between $3 million to $5 million per route-mile. (This assumes one new lane in each direction.) Full widening within available right-of-way could cost $8 million to $15 million or more per route-mile. Barrier separated treatments are much more expensive than contiguous lane treatments because of the extra shoulder requirements.

Enforcement represents the most common and significant ongoing operation and maintenance cost over and above the initial investment in regional traffic management. Enforcement costs vary widely depending on the facility type, and enforcement costs are often the most significant during the first six months of a new facility opening.

1.13. Phasing

A managed lane facility is often part of a larger transportation investment program for a corridor, and each facility becomes a part of an overall plan that could include a variety of other improvements. These opportunities often set the stage to develop an implementation plan. Stand-alone plans could also be developed for a “managed lane network.”

Some regions have oriented a phasing plan on implementing projects of opportunity first, with a focus toward adding a managed lane along a corridor. The region then adds access and safety enhancements as demand warrants. This context builds on two premises.

- Adding a managed lane before adding transit or access improvements is usually more cost effective to achieve early benefits so long as the link being added is long enough to provide meaningful time savings to generate demand.
- If demand does not materialize in some areas, it is easier to take the HOV or HOT restriction away and convert the managed lane into a general-purpose lane if direct-access investments are not included.

More commonly, enhancements are added as managed lane demand grows and lane capacity is reached.

Phasing for a first managed lane facility in any region sets the stage of the overall public perception and could affect the success of a managed lane strategy for many years. If the first facility is a success, there is less scrutiny on subsequent expansion. If the facility fails, there is a lower likelihood that the public would support another facility. While few facilities have actually “failed” or been terminated over the past 30 years, some have been marginalized to the point that they are no longer viable in meeting their original goals. To address this, goals potentially need to change over time to meet evolving commute and demand requirements. The most common pitfalls relate to a lack of congestion, inadequate demand, too much demand, existence of a toll cap that restricts the ability to set a higher price, and relaxed enforcement.

Ideally, the initial phase(s) of an overall plan is to address the region’s most significant congestion bottleneck, to serve transit and rideshare needs, and to generate an early level of acceptable demand. All of this is to be supported by a variety of local partnering agencies at all levels. While not all of these factors must exist, each complement one another and make the role of marketing more effective with different stakeholders so that all recognize the benefits of the managed lanes.

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2.0. RAMP METERING

2.1. Ramp Metering Warrant Analysis

This section presents standardized procedures and guidelines that can be used to determine if ramp metering is warranted at a candidate on-ramp. First, the two issues (safety and congestion) that lead to consideration of ramp metering are discussed. Next, a systematic ramp metering warrant process is described for application to ramps that are being considered for metering.

2.1.1. Problem Analysis

The implementation of a ramp meter is often based on existing conditions and/or problems that would be improved or mitigated with ramp metering. However, the decision to implement a ramp meter cannot be only based on the problems it addresses, but rather the decision must also account for feasibility of implementation and whether or not the ramp metering is the best solution when compared to other solutions.

2.1.1.1. Safety

High collision rates in the vicinity of a ramp/mainline merge area could warrant a ramp meter to improve traveler safety. Of particular importance are collisions linked to ramp operations, including rear-end collisions in the vicinity of ramp/mainline merge areas. High collision rates at these locations often indicate that freeway operations are being jeopardized by the quantity or manner in which vehicles are entering the freeway. Analysis of recent collision rates, by total collisions and by collision type, is to include the entire freeway length for which ramp meters are proposed. Analysis results provide conclusions on whether collisions are more prevalent at a single ramp or within a longer section of the freeway. Based on this, the geographic scope of the ramp metering program is determined.

Rear-end collisions frequently occur on entrance ramps and at points upstream from the ramp/mainline merge points as a result of poor operations at the ramp/mainline merge point. Vehicles that enter congested freeways in platoons cause the mainline traffic at the merge point to slow down. For motorists upstream of the ramp/mainline merge point, who may be unaware of slowing traffic, this reduction in speed regularly occurs sharply. If an adequate following distance is not used, or if other conditions are present that affect the braking distance or reaction time, rear-end collisions occur. Similarly, the same situation applies to motorists traveling on the entrance ramp who have yet to approach the ramp/mainline merge point. Ramp metering could reduce the number of rear-end collisions on both the ramp and at points upstream of the ramp/mainline merge point by enabling vehicles to enter the freeway more smoothly.

Similar to rear-end collisions, sideswipe and lane change collisions at or immediately downstream of ramp/mainline merge areas could also be reduced through ramp metering. Merging traffic often forces their way into smaller gaps or drivers already on the freeway tend to swerve to avoid a collision or make an unsafe lane change when large platoons enter from a ramp. By splitting up the platoons, ramp metering allows ramp traffic to find a safe gap to enter, and drivers already on the freeway are more able to respond to the merging traffic.

2.1.1.2. Congestion

High collision rates and incidents are the major causes for freeway congestion. Other causes include bottlenecks, geometric deficiencies (including those that limit motorists' ability to smoothly enter the freeway), increases in demand (i.e., entering demand that exceeds exiting demand), and vehicle queuing on exit ramps that spill back onto the freeway. Knowing the cause of congestion is critical before selecting any type of ramp management strategy. In some cases, ramp metering is not applicable or less favored when considered side-by-side with other types of strategies.

Freeway LOS or freeway speed is a good indicator of whether or not a freeway or a segment of the freeway is congested. Freeway conditions at LOS D or worse are candidates for ramp metering; however, other existing problems and the appropriateness of alternate improvements and management strategies are to be evaluated. There are geometric, traffic, and system-based conditions when a ramp meter could be beneficial at LOS C (when an urban freeway is not considered congested).

Low freeway speeds suggest a problem. Low speeds could happen because traffic from one or more ramps is entering the freeway in platoons or because the overall demand on the freeway exceeds its capacity.

Travel time is another indicator of congestion. Actual travel time measurements can be compared with travel times collected under ideal conditions (i.e., free-flow) to assess the impact congestion is having on travel. Travel time reliability is also an important measure of congestion. More predictable travel times offer users more consistent travel schedules and a further likelihood of avoiding unexpected delays. Ramp metering has been shown to reduce travel times and improve travel time reliability.

2.1.2. Systematic Warrant Process

This section presents a systematic warrant process that builds upon the problem analysis described above. The warrant analysis for determining the need for a ramp meter consists of two steps. The first step is the evaluation of individual warrants. The second step is to systematically analyze the individual warrants in a decision tree to complete the assessment. Of note, ramp metering is rarely applied at a single isolated interchange. Instead, a system approach over a length of freeway is recommended when considering ramp meter evaluation and application.[17]

2.1.2.1. Individual Warrants

Table 2-1 lists the individual warrants to evaluate as a first step of the warrant analysis. Upon evaluation of the individual warrants, an overall ramp metering warrant analysis is completed as described in Section 2.1.2.2.

Warrants 2, 3, and 4 correlate with safety and congestion aspects of the freeway, and at least one of these warrants is to be met to justify a ramp meter. Warrants 1, 5, 6, and 7 (i.e., volume warrants) serve a secondary purpose to ensure that a ramp meter is not installed at locations with low volumes. At such locations, even if safety and congestion issues exist, ramp metering is not the ideal solution, and other mitigation measures are to be examined. Ramps where problems have been observed are evaluated in greater detail to understand the problems better, to assess whether or not ramp metering best addresses these problems, and to determine the feasibility of deploying a ramp meter.

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[17] See Section 2.2 for additional information.

Before a decision is made to install a ramp meter, it must first be determined if poor geometry is the cause of the observed problems at the ramp. Closely spaced ramps with weaving problems, limited sight distances, narrow shoulders, and narrow lane widths are some examples of issues related to poor geometry. Fixing any geometric deficiency could alleviate problems observed at the ramp, and ramp metering may not have to be implemented.[18]

Warrants 8 and 9 support the geometric feasibility of ramp meter installation at a proposed location. Meeting Warrant 8 (acceleration length) is critical. If acceleration length is inadequate, safety on the ramp, along the freeway, or at the merge area could be jeopardized. First, vehicles entering the freeway at speeds lower than on the mainline frequently force vehicles approaching the freeway/ramp merge point to slow down or change lanes to allow vehicles from the ramp to enter safely. As a result, rear-end and sideswipe collisions could occur at locations immediately upstream of the freeway/ramp merge point. In some cases, slow moving vehicles entering from a ramp are forced to wait for gaps in mainline traffic at the freeway/ramp merge point before entering the freeway. This action could contribute to sideswipe collisions at the freeway/ramp merge point, as well as rear-end collisions on the ramp. Therefore, if adequate acceleration length to safely merge with mainline traffic cannot be provided, a ramp meter is not to be installed, even if other warrants are met.[19] Similarly, lack of adequate storage length (Warrant 9) could preclude the use of a ramp meter. However, unlike acceleration length, installing a ramp meter could still be the preferred solution despite the storage issues. Such cases are to be discussed with NDOT and the local agencies.

2.1.2.2. Overall Ramp Metering Warrant

Overall ramp metering warrant analysis is to be completed after evaluating the individual ramp warrants. Not all warrants have to be met for justifying the installation of a ramp meter. The overall ramp metering warrant ensures that installation of a ramp meter at a location is based on whether the various individual ramp metering warrants are satisfied at a particular location. The overall ramp metering warrant also verifies that all installation decisions are based on the considerations explained in the previous sections.

A low-volume ramp or a ramp where metering is not warranted individually could receive a ramp meter if it lies within a system of freeway ramps with ramp meters (i.e., system approach). On the other hand, meeting the warrants does not in itself require the installation of a ramp meter. Figure 2-1 illustrates the step-by-step process for completing an overall ramp metering warrant analysis.

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[18] For certain cases, ramp metering could still be the solution if fixing the geometric deficiency is less cost-effective.

[19] See Part 3: Design Manual for acceleration length requirements.

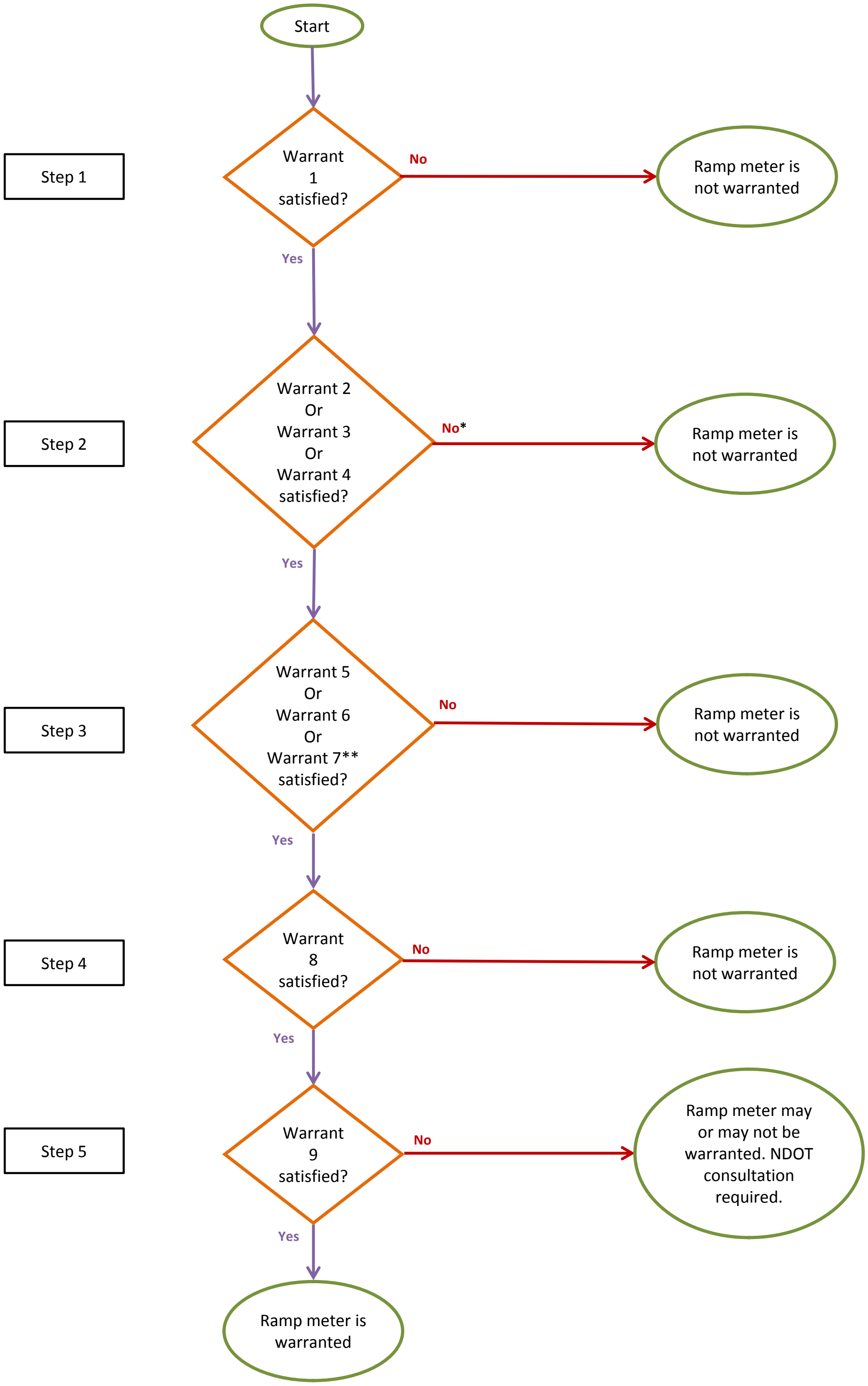
Table 2-1: Ramp Metering Warrants (Individual Warrants)

Number	Name	Description
1	Ramp Volume Warrant (Ramp Volume)	Is the ramp volume during the critical peak period greater than 240 vehicles per hour per lane (vphpl)? 240 vphpl is the practical lower limit for ramp metering.
2	Safety Warrant (Crash Rate)	Is the rate of crashes at the ramp gore point or within 500 feet in either direction of the gore point greater than the mean crash rate for comparable sections of freeways in the metropolitan area?
3	Operational Warrant 1 (Speeds)	Does the freeway operate at speeds less than 50 mph for duration of at least 30 minutes for 200 or more calendar days per year?
4	Operational Warrant 2 (LOS)	Does the freeway operate at LOS D or worse during the peak period?
5	Volume Warrant 1 (Mainline Volume* and Ramp Volume)	Does the total volume* downstream of the gore during the peak period exceed the following? ♦ Two mainline lanes in one direction – 2,650 vehicles per hour (vph) ♦ Three mainline lanes in one direction – 4,250 vph ♦ Four mainline lanes in one direction – 5,850 vph ♦ Five mainline lanes in one direction – 7,450 vph ♦ Six mainline lanes in one direction – 9,050 vph ♦ More than six mainline lanes in one direction – 10,650 vph
6	Volume Warrant 2 (Mainline Right Lane Volume and Ramp Volume)	Is the ramp volume plus the mainline right lane volume downstream of the gore during the peak period greater than 2,100 vph?
7	Platoon Warrant (Platoons from Signalized Intersections)	Is the hourly volume entering from arterials, based on highest 30-second volume readings (during the critical peak period) projected to hourly values, greater than 1,100 vph?
8	Geometry Condition 1 (Acceleration Length)	Is the available or proposed acceleration length after the stop bar longer than the required acceleration length, or can geometric improvements be made to provide the required length?**
9	Geometry Condition 2 (Ramp Storage Length)	Is the available or proposed ramp storage length greater than the estimated queuing length on the ramp, or can geometric improvements be made to provide the required length?**

* Managed lanes are excluded. Only general-purpose lanes and auxiliary lanes that continue at least 1/3 mile downstream from ramp gore are included.

**Depending on the existing geometric conditions, and the required acceleration length and ramp storage length estimated for Warrants 8 and 9; geometric improvements may be needed prior to the implementation of the ramp meter.

Figure 2-1: Ramp Metering Warrant Analysis



* Refer to Section 2.1.2.2.

** Use engineering judgment if Warrant 7 is the only volume criterion that is satisfied. NDOT consultation recommended.

2.1.3. Warrant Analysis Example

The following is an example of a hypothetical ramp meter warrant analysis that assumes the freeway and the on-ramp have the following characteristics.

- There are four lanes of mainline downstream of the gore.
- Total mainline critical peak hour volume downstream of the gore is 4,930 vph.
- The rate of crashes within 500 feet of the gore point is more than the mean crash rate for comparable sections of freeways in the metropolitan area.
- Mainline speed is maintained above 50 mph throughout the day for a majority of the days surveyed.
- The freeway operates at an LOS C during the critical peak period.
- The mainline right lane plus ramp volume during the critical peak hour is 2,330 vph.
- The maximum 30-second volume entering the ramp/freeway from the arterial during the critical peak hour is 11 vehicles.
- Ramp volume during the critical peak hour is 1,030 vph.
- Adequate geometry is available for storage and acceleration length.

Based on these ramp characteristics, Table 2-2 lists the results for each individual warrant.

Table 2-2: Warrant Analysis Example

Warrant Number	Warrant Satisfied?
Warrant 1	Yes
Warrant 2	Yes
Warrant 3	No
Warrant 4	No
Warrant 5	No
Warrant 6	Yes
Warrant 7	Yes
Warrant 8	Yes
Warrant 9	Yes

In line with the individual warrants analysis, the following are the results from the overall warrant analysis.

- Step 1: Answer is “Yes,” proceed to next step.
- Step 2: Answer is “Yes,” proceed to next step.
- Step 3: Answer is “Yes,” proceed to next step.
- Step 4: Answer is “Yes,” proceed to next step.
- Step 5: Answer is “Yes,” so a ramp meter is **warranted** at the on-ramp.

2.2. Location Analysis

The geographic extent of ramp metering is largely based on existing problems, and whether or not these problems are confined to a single ramp, or exist at several locations along a corridor or within several corridors. The geographic extent of ramp metering is also influenced by jurisdictional and political boundaries, the ability to limit diversions, and the extent of recurring congestion.

2.2.1. Single Ramp versus System Approach

Ramp meters are typically deployed as a system (i.e., multiple ramps) as opposed to implementing a single ramp meter. If traffic or safety problems on a freeway are isolated (i.e., the problems occur at specific locations not adjacent to each other, and control at a single ramp solves or sufficiently reduces the problems), ramp meters could be used independently. However, any time a meter is deployed, the potential exists for impacts to arise (see Section 2.3). If a single ramp meter installation would have impacts at other locations, a system approach is required.

Depending on the extent of the problem(s), meters would be implemented along a freeway segment, an entire corridor, or several corridors to effectively address the problem(s). To be truly effective, ramp metering is to be implemented with logical system ramp meter terminal points.

2.3. Impact Analysis

Potential impacts of a ramp meter on existing conditions and operations must be thoroughly assessed before deciding where and if to implement a meter. This process includes analyzing impacts to the ramp terminal intersection, traffic patterns (e.g., diversion and queuing), impacts to adjacent neighborhoods, and safety impacts.

Sketch planning tools (e.g., Intelligent Transportation System [ITS] Deployment Analysis System [IDAS]) estimate the effects of ramp metering. Understanding the existing situation, problem, and estimated impacts assists in establishing if ramp metering offsets the potential impacts after implementation. If ramp metering offsets impacts, ramp metering is then compared against other appropriate strategies before deciding on the best strategy or strategies for implementation. It is possible that metering is not the best improvement option when compared against other ramp management strategies.

In addition to analyzing ramp queues, ramp delays, and mainline impacts, an assessment of diversion, equity, and public perception must also be analyzed.

2.3.1. Diversion

Ramp metering could result in a portion of the existing traffic being diverted from freeways to arterials or from a metered ramp to an alternate ramp. As such, users can elect to bypass queues that form on metered ramps by using arterials that parallel a freeway. This is especially true for users who take short trips, in which case wait times at a ramp meter could exceed the additional travel time that results in slower arterial speeds. Diversion from one ramp to another can increase the vehicle miles traveled on the network and vehicle hours of delay for the roadway system.

Diverted traffic could be a problem depending on available capacity on routes able to carry the additional traffic. If a sufficient number of routes are available and if diversion could be accommodated at downstream ramps, diversion is a benefit because it provides a more efficient use of existing capacity.[20] However, if available routes cannot support diverted traffic, operations on nearby arterials are likely to be negatively affected. This could also lead to jurisdictional disputes and conflicts because ramp and arterial facilities are typically managed by different agencies. One agency's operations could negatively impact another agency's operations.

If diversion cannot be easily accommodated on the arterial network, if the diversion would carry traffic through neighborhoods or other sensitive areas, or if diversion is a sensitive issue, then NDOT and its partner agencies are to consider ways to reduce delay times, accommodate diversion by making improvements on alternate routes, or both. If there are no means to accommodate or reduce the likelihood of diversion to an acceptable level, ramp metering is probably not feasible. If the agencies are unsure of the impact of diversion, a pilot metering implementation could be used to determine the diversion level and impact.

2.3.2. Equity

When analyzing the appropriateness of ramp meters for specific ramps, NDOT is to consider the distribution of benefits and drawbacks of ramp metering and operations before implementing ramp meters. A ramp meter could produce benefits for some users at the expense of others. This is viewed as unfair and is politically unfavorable.

A way to address the concerns of equity is to make sure ramps that carry a significant amount of traffic into the congested area are metered, even if congestion does not reach that ramp. Origin-destination studies or estimates are the best ways to determine if a significant number of travelers from unmetered ramps receive an undue benefit.

Equity can also be addressed when setting metering rates or establishing the parameters in an algorithm that calculates or selects metering rates. Those who benefit the most from mainline travel time savings would potentially be willing to experience the most delay on the ramps.

2.3.3. Public Perception

Potential public opposition to ramp metering is to be taken into account, and strategies for improving public perception are to be developed. It is probable that a certain percentage of the public would perceive ramp metering as not a viable solution. In addition, these individuals could focus on the few negative aspects of a ramp meter and fail to realize that the negatives are typically offset by the benefits of a ramp meter. A proactive program to disseminate information and to demonstrate metering benefits is necessary. This includes outreach to other agencies, local businesses, and the media. Without public support, ramp meters could be viewed as costly and ineffective. This, in turn, could lead to problems with receiving funding to expand the system or to support ongoing operation and maintenance of the system.[21]

Notably, ramp metering has had significant positive support and public acceptance in the urban Las Vegas area where metering has been in operation for several years. Opinion surveys

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[20] Measures such as traffic calming techniques are to be in place to prevent diverted drivers from using local neighborhood streets.

[21] Recommended approaches for outreach and public information are presented in Part5: Public Outreach Primer.

conducted by the Regional Transportation Commission of Southern Nevada (RTC) found 90 percent of drivers like the ramp meters to be operating.

2.4. Ramp Metering Approach

2.4.1. Local versus Coordinated/System-Wide Control

Ramp meters can operate either isolated from one another (local control) or as part of a larger system (coordinated or system-wide control).

2.4.1.1. Local Control

Local control is a process of selecting ramp meter rates based solely on conditions present at an individual ramp (upstream, downstream, or at the merge point). This approach does not consider conditions along a segment of freeway, along a freeway corridor, or in association with anywhere else on the freeway network. When local control is used, no effort is made to coordinate the effects of various ramp meters. The primary concern is improving conditions and reducing congestion near the ramp itself. In some cases, when local control is used, congestion problems at the ramp appear to be resolved. However, this could just shift the problems to other locations. In these situations, local control is not recommended.

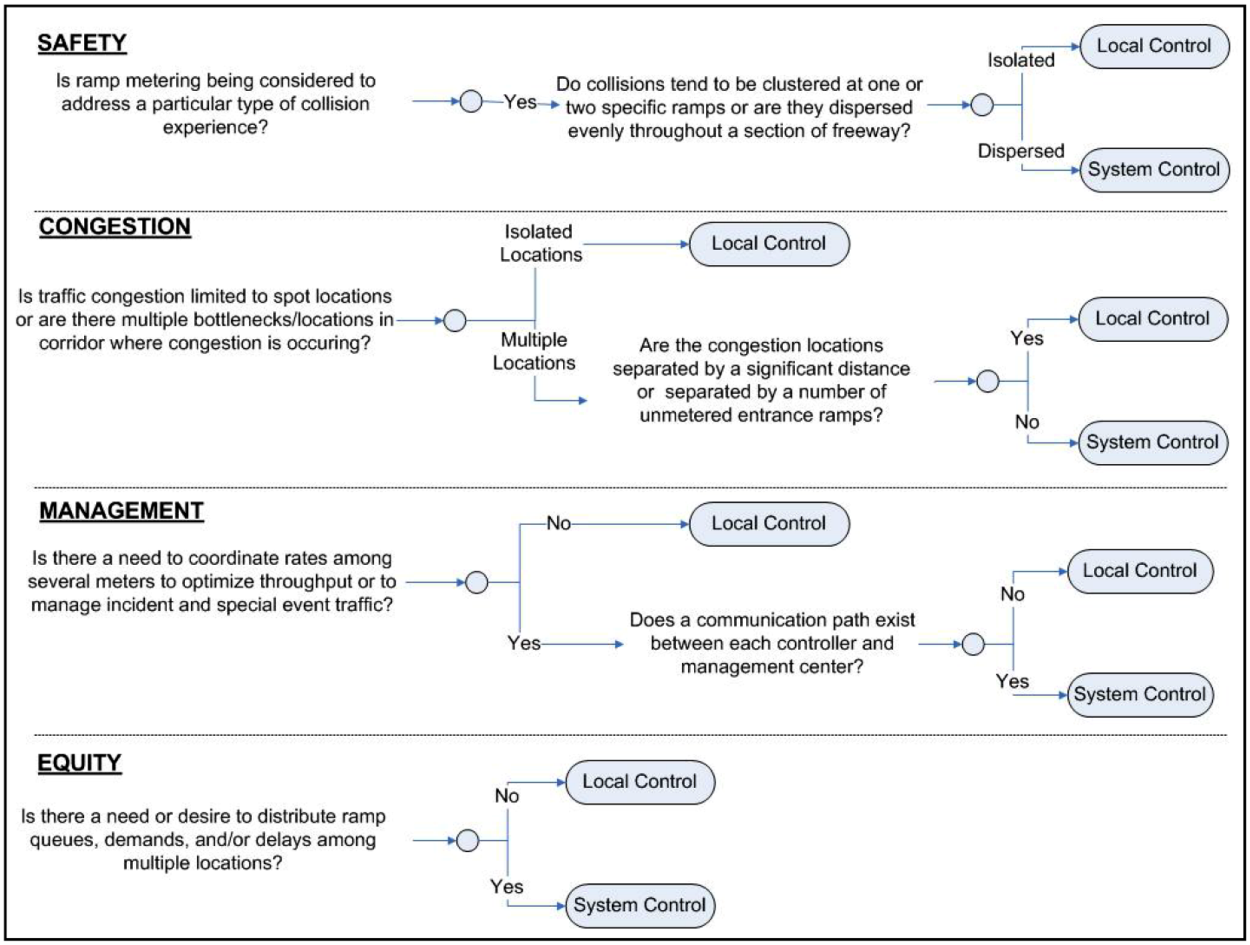
2.4.1.2. Coordinated/System-Wide Control

Coordinated or system-wide control is a process of selecting metering rates based on conditions throughout the metered corridor. Coordinated control accounts for conditions beyond those adjacent to the ramp when determining metering rates for an individual ramp. To this extent, coordinated control applies across a freeway segment, an entire corridor, or several freeway corridors. The primary focus centers on improving freeway conditions for an entire segment, corridor, or region. Compared to local control, this allows flexibility with coordinated control in handling reductions in capacity that happen as a result of delay, collisions, and road blockages.

Figure 2-2 provides guidance as to whether to operate a ramp meter under local or system-wide control.

It is recommended that the traffic signal timing at the ramp terminal intersection be coordinated with the ramp meter timing. This allows for adjustments to the metering rate based on the conditions at the ramp terminal intersection. Similarly, it allows for adjustments to the signal timing at the ramp terminal intersection based on the conditions on the ramp.

Figure 2-2: Local versus System-Wide Control



Source: Operating Guidelines for TxDOT Ramp Control Signals.

2.4.2. Pretimed versus Traffic Responsive Control

When the decision has been made to install a ramp meter, NDOT, in coordination with the operating agency, would decide whether a meter is to be pretimed or traffic responsive. The selection of either approach is independent of the decision to implement local or coordinated control.

The primary consideration for selecting pretimed or traffic responsive metering is the ability to install traffic detectors. If NDOT cannot install traffic detectors on the ramp and mainline, traffic responsive metering cannot be used. Another factor that may affect selection is cost. At first glance, it may seem that traffic responsive metering has a higher cost because there are more components to install (e.g., loop detectors and sensors) and the systems appear to be more complex. However, these costs are typically offset by the day-to-day monitoring and operating tasks associated with pretimed meters.

2.4.2.1. *Pretimed Control*

Pretimed control is best used when traffic problems are a direct result of recurring congestion or when localized safety problems could be reduced by simply breaking up queues of vehicles entering the freeway. This is because pretimed metering rates are based on historical data and, unlike traffic responsive systems, cannot make adjustments for real-time conditions, including non-recurring congestion. Because metering rates cannot adjust to real-time conditions, rates may be too fast or too slow for current conditions. Despite this, pretimed systems are often an easy-to-implement, low-cost approach, and it is the low capital costs that make the pretimed control attractive.

2.4.2.2. Traffic Responsive Control

Traffic responsive metering systems use data from freeway loop detectors or other surveillance systems to calculate or select ramp metering rates based on current freeway conditions. Real-time traffic data is fed into an algorithm that selects the appropriate metering rate.

Local traffic responsive metering rates are determined based on freeway conditions at the metered ramp (upstream, downstream, or at the merge point). Detectors are placed on the ramp, and upstream and downstream of the merge point within the vicinity of the ramp. Metering rates are determined independently of all other ramps. Local traffic responsive control is a proven strategy that is often used as a backup when communication fails with a central control system.

Coordinated (system-wide) traffic responsive systems optimize traffic flow along a metered stretch of roadway versus a specific point on the freeway (as is the case of local traffic responsive systems). Coordinated traffic responsive systems operate similar to local traffic responsive systems; however, coordinated approaches base metering rates on conditions throughout a section of the freeway. As such, metering rates at any given ramp are influenced by conditions at other metered ramps within the system or corridor. Similar to local traffic responsive systems, coordinated traffic responsive systems require data from ramp detectors and mainline freeway detectors. In addition to these components, coordinated traffic responsive systems are unique in the fact that data is also needed from downstream detectors, upstream detectors, and detectors at other ramps. Communication to a central computer is required with this system, and coordinated traffic responsive systems have the most complex hardware configuration of all the metering approaches discussed.

2.4.3. Summary of Ramp Metering Approaches

Table 2-3 summarizes the various features of ramp metering approaches.

Table 2-3: Summary of Ramp Metering Approaches

	Pretimed	Traffic Responsive
Local	◆ Appropriate for localized problems. ◆ Detection in the field is not needed. ◆ Requires periodic manual updates. ◆ Not effective for dynamic conditions. ◆ Higher operations costs compared to traffic responsive systems. ◆ No communication with a TMC is required. ◆ Simple hardware configuration compared to traffic responsive approaches. ◆ Provides a safety benefit by breaking up a platoon of vehicles entering the freeway. ◆ Can effectively relieve recurring congestion if it is fairly constant from one to the next. ◆ Requires frequent observations so rates can be adjusted to changing traffic conditions. ◆ Often results in over-restrictive metering rates that lead to unneeded ramp queuing and delays, which could affect arterial operations as well. ◆ Not responsive to unusual conditions, such as nonrecurring congestion.	◆ Appropriate for localized problems. ◆ Detection in the field is needed. ◆ Higher capital and maintenance costs compared to pretimed systems. ◆ Yields greater benefits because it responds to conditions in the field. ◆ Ability to better manage freeway congestion than pretimed metering approaches (especially for non-recurring congestion). ◆ Operating costs are lower than pretimed (because of automatic, rather than manual, meter adjustments) so the extra investment upfront could pay itself off over time. ◆ Improvements are made after the fact, rather than before problems occur. ◆ Does not consider conditions beyond the adjacent freeway section, making it difficult to optimize conditions for a downstream bottleneck.
Coordinated	◆ Appropriate for widespread problems. ◆ Detection in the field is not needed. ◆ Rarely used compared to coordinated, traffic responsive systems. ◆ No communication with a TMC is required. ◆ Simple hardware configuration compared to traffic responsive approaches. ◆ Provides safety benefit by breaking up a platoon of vehicles entering the freeway. ◆ Can effectively relieve recurring congestion. ◆ Requires frequent observations so rates can be adjusted to changing traffic conditions. ◆ Often results in over-restrictive metering rates that lead to unneeded ramp queuing and delays, which could affect arterial operations as well. ◆ Not responsive to unusual conditions.	◆ Appropriate for widespread problems. ◆ Detection in the field is needed. ◆ Most useful for corridor applications. ◆ Greatest capital and maintenance costs, but yields most benefits. ◆ Provides optimal metering rates based on real-time conditions throughout the system or corridor. ◆ Requires mainline detection (both downstream and upstream detectors). ◆ Requires communication to central computer. ◆ Requires technical expertise for calibrating and implementing system. ◆ More expensive than local traffic responsive in implementation resources needed and communications maintenance.

Source: FHWA's *Ramp Management and Control Handbook*.

2.4.4. Operator Control

Operator control/selection is a method, initiated by an operator, to select a metering rate based on prevailing conditions. Usually, operator selection addresses special conditions where traffic patterns and volumes are not as predictable.

2.5. Ramp Metering Algorithms

Various ramp metering algorithms are available for implementation. For pretimed control, the algorithm is simply called "clock-time," where the meter operates at a set rate for the times and days specified by the user. For traffic responsive control, the available algorithms are broadly divided into two categories: "open loop" and "closed loop."[22]

In open loop algorithms, the metering rate is independent of the other metered ramps and mainline locations along the corridor. Traffic conditions on the ramp and in the immediate vicinity of the ramp are used to generate the timing plans for the meter. Hence, open loop algorithms are only applicable to *local* traffic responsive control. Examples of open loop algorithms are as follows.

- **Speed control.** Metering rate is determined based on the speed measurements from the detectors immediately upstream and downstream of the ramp (usually upstream only).
- **Demand capacity control.** This algorithm's purpose is to regulate the downstream mainline volumes such that the capacity is not exceeded at the merge area. If the upstream volume exceeds the downstream capacity, the minimum metering rate is applied to ensure that the congestion does not occur downstream.
- **Upstream occupancy control.** This algorithm is similar to the speed control with the exception that the upstream occupancy data is used instead of the upstream speed data to determine the metering rate.
- **Gap occupancy control.** In this algorithm, the signal turns green when there is an available gap in the merge lane. Available gap is based on occupancy measurements taken at the upstream detectors.

In closed loop algorithms, the metering rates are established based on inputs from the entire system. Generally, closed loop algorithms are applicable to *system-wide* traffic responsive control. Examples of closed loop algorithms are as follows.

- **Bottleneck algorithm.** The objective of this algorithm is to confirm that traffic entering the bottleneck area does not exceed capacity. Metering rates are set such that the difference between vehicles released from all upstream ramp meters and the upstream mainline locations is less than the bottleneck capacity.
- **Fuzzy logic algorithm.** This algorithm is developed to minimize total travel time and delay.

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[22] The algorithms that FAST currently use for Las Vegas area ramp meters are expanded upon in Section 2.12 of this document.

2.6. Flow Control Scheme

Flow control scheme is the general term used for the configuration of how a ramp meter permits vehicles to enter a freeway. When flow controls are implemented on a ramp, the throughput capacity is reduced, and excess demand is held on the ramp.

Flow control scheme is a combination of the metering release rate (Section 2.6.1) and number of storage lanes on the ramp (Section 2.6.2). Expanded upon in the subsequent sections, ramp meters employ one of the following flow control schemes.

- **Single lane, one car per green.** Permits a single vehicle to enter the freeway per cycle for one lane only.
- **Single lane, two cars per green.** Permits two vehicles to enter the freeway per cycle, for one lane only.
- **Dual lane, one car per green.** Permits a single vehicle to enter the freeway per cycle, per lane.
- **Dual lane, two cars per green.** Permits two vehicles to enter the freeway facility per cycle, per lane.
- **Triple lane, one car per green.** Permits a single vehicle to enter the freeway per cycle, per lane.
- **Triple lane, two cars per green.** Permits two vehicles to enter the freeway per cycle, per lane.

The flow control scheme primarily depends on the practical capacity of the metered ramp and available storage on the ramp. When there is not adequate capacity and/or storage with the “single lane, one car per green” scheme, “dual lane, one car per green” or “triple lane, one car per green” schemes are considered. If additional storage lanes are not available or the available length is not adequate, a “two cars per green” scheme could be applied, subject to NDOT approval.

2.6.1. Metering Release Rate

2.6.1.1. One Car per Green

“One car per green” metering permits vehicles to enter the freeway one vehicle at a time per green indication. For pretimed systems, one car per cycle length is allowed. For traffic responsive systems, when a vehicle approaches the ramp meter, it passes over the presence detector, which notifies the signal to turn green. As a vehicle passes over the passage detector, the signal is then notified to terminate the green cycle. If a vehicle is not present, the signal indication remains red until a vehicle is detected. “One car per green” is the standard release rate for every ramp meter in the State.

2.6.1.2. Two Cars per Green

The “two cars per green” approach allows two vehicles to enter the freeway per green indication. Allowing two vehicles per green is also referred to as a dual release rate. Although this approach doubles the throughput of vehicles per green indication, proportionate results cannot be expected for vehicle throughput because longer cycle lengths are required. “Two cars per green” could be considered, subject to NDOT approval, as a queue management technique. However, the design for new facilities and the adequate number of lanes and storage lengths must be based on the standard "one car per green" release rate.

2.6.2. Number of Storage Lanes

2.6.2.1. *Single-Lane Metering*

Single-lane metered ramp design could accommodate single or dual vehicle release rates depending on the desired flow rate.

2.6.2.2. *Multi-Lane Metering*

Multi-lane metered ramps are used to increase overall vehicle storage within the available ramp length or to accommodate demands that exceed the capacity of a single metered lane.

Multi-lane metering releases vehicles alternating between the lanes. Simultaneous or independent release of vehicles is generally not used, and is only approved when adequately justified and at the sole discretion of NDOT.

Table 2-4 lists the characteristics associated with each flow control scheme. The table assumes only "one car per green" schemes. The cycle lengths shown are the typical cycle lengths for pretimed metering because the cycle length is variable for traffic-responsive systems. The capacities are based on actual practical capacities observed on the existing ramp meters in the State.

Table 2-4: Types and Characteristics of Ramp Metering Flow Controls

Flow Control Scheme	Cycle Length	Capacity (Hourly Discharge Rate)
Single Lane, One Car per Green	4 to 4.5 seconds	750 to 800 vehicles
Dual Lane, One Car per Green	4 to 4.5 seconds	1,500 to 1,600 vehicles
Triple Lane, One Car per Green	6 to 6.5 seconds	1,500 to 1,600 vehicles

2.7. HOV Bypass Lane

To encourage the use of carpools, vanpools, and transit, an HOV bypass lane could be added to a metered ramp to allow occupants of these modes to bypass queues that form as a result of metering. It is recommended that an HOV bypass lane be installed at every urban ramp where ramp metering exists.

HOV bypass lanes are not to be implemented under the following conditions.

- Retrofit project where an HOV bypass lane cannot be provided within the existing right-of-way, unless right-of-way acquisition is planned as part of the improvement at that ramp.
- If three general-purpose lanes are required for providing the required storage length, an additional HOV bypass lane, to make a total of four lanes, is not to be considered.

- Roadway geometrics cause an SOV to inadvertently be trapped in an HOV lane.[23]
- Roadway geometrics do not safely allow HOVs to merge into the HOV bypass lane.[24]

HOV bypass lanes are to be metered. The purpose of the HOV designation is to allow HOVs to bypass the queues (i.e., get in front of the queue).

The left side of the ramp is the typical location for an HOV bypass lane. However, demand and operational characteristics could dictate a more efficient lane orientation. It is recommended that the right turn movement from the arterial to the metered ramp be analyzed. If there is a large volume of right turning traffic that includes significant HOV volumes, the configuration that minimizes HOV delay and weaving is the most optimal option. If the right lane from the arterial is an exclusive right-turn lane to the ramp and serves significant HOV volumes, then a preference would be to locate the HOV bypass lane on the right side. This would prevent the high volumes of HOVs from weaving to the left lane on the ramp. In any case, right side HOV lanes would be approved only when adequately justified and at the sole discretion of NDOT.

2.8. Determining Number of Lanes to Meter

The number of required lanes on a metered ramp is determined from the ramp peak hour volume demand. For new facilities, the number of lanes to meter is to be based on the projected peak hour ramp demand volume for 20 years after opening. For existing facilities (i.e., retrofitting a ramp meter), the number of lanes to meter is to be based on the highest among current, projected 5-year and 20-year peak hour demand volumes. Assuming 20-year volumes are the highest among the three (which is oftentimes the case), less than projected 20-year volumes could be approved case by case and at the sole discretion of NDOT. However, for such cases, design must always account for current and 5-year volumes.

Table 2-5 provides guidelines for establishing the required number of lanes to meter. The upper limit for traffic volumes on a single lane is 800 vph because this is the practical capacity of a single-lane ramp meter. The 240 vph is the lower limit because this is the lower volume threshold for a ramp meter to be warranted.

Table 2-5: The Required Number of Lanes to Meter

Ramp Peak Hour Volume (vph)	*Required Number of Lanes*
240 to 800	Single lane
Greater than 800	Dual lanes*
* Three lanes are required if dual lanes cannot accommodate the calculated storage length. In cases where three lanes are required for storage, an additional HOV bypass lane is not to be considered (i.e., four lanes are not an option).	

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[23] Simply not providing an HOV bypass lane is not acceptable under this condition. There are appropriate treatment options to avoid SOVs that inadvertently become trapped in the HOV lane (see Part 3: Design Manual).

[24] Simply not providing an HOV bypass lane is not acceptable under this condition. There are appropriate treatment options to ease access to the HOV lane (see Part 3: Design Manual).

As shown in Table 2-4, the practical metering capacity of a two-lane and three-lane ramp is the same. Therefore, a three-lane ramp meter is recommended only for situations where a two-lane ramp cannot accommodate the calculated queues.[25]

2.9. Freeway-to-Freeway and Collector-Distributor Road Metering

Freeway-to-freeway metering consists of metering a ramp that connects one freeway to another. Freeway-to-freeway ramp metering could be used when it is more advantageous to meter a freeway spur than nearby entrance ramps upstream of the location where the two freeways connect. While not currently implemented in Nevada, metering freeway-to-freeway connectors could be considered. Such metering is to be discussed with NDOT and is subject to Traffic Operations Division review and approval. FHWA's *Ramp Management and Control Handbook* provides guidelines for implementing freeway-to-freeway ramp metering.

Collector-distributor (C-D) road metering consists of metering a ramp that connects a C-D road to a freeway. While not currently implemented in Nevada, metering C-D roads could also be considered in the future.

2.10. Ramp Storage and Queues

Queue lengths (i.e., required storage lengths) are calculated based on the hourly demand volume on the ramp, arrival rates, number of lanes on the ramp, discharge rate, and average vehicle length. The arrival and discharge rate is calculated based on a 140-second cycle length. As shown in Table 2-4, hourly discharge rate is 800 vph for a single-lane ramp meter and 1,600 vph for a dual or triple-lane ramp meter. These correspond to a "per 140-second cycle length" discharge rate of 31 and 62 vehicles. The basic premise of the methodology is that if the arrival rate is greater than the discharge rate, a queue builds up. The subsequent steps further articulate the methodology to calculate the required storage length at a candidate ramp meter location.

- **Step 1.** Obtain 20 year projected peak hour ramp demand volume.
- **Step 2.** Calculate 140-second arrival rates (rounded up to the next integer) using a peak hour factor of 0.80.
- **Step 3.** Determine the required number of lanes based on the guidance provided in Table 2-5.
- **Step 4.** Calculate excess vehicles per 140-second cycle length by subtracting the discharge rate (i.e., 31 for single lane and 62 for dual lane) from the arrival rate.
- **Step 5.** Calculate total queue length by multiplying the excess vehicles by a vehicle spacing of 30 feet.
- **Step 6.** Calculate queue length per lane by dividing the calculated total queue length by the number of lanes.
- **Step 7.** Calculate the required storage length per lane by adding the minimum storage length to the calculated queue length by lane.* The calculated storage length is to be

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[25] Queue length calculations are explained further in Section 2.10.

rounded up to a multiple of 30. Additional storage must be provided if there are significant number of trucks, buses, or RVs using the ramp.

*In cases where the discharge rate is greater than arrival rate, a minimum storage length is required. This minimum storage length accounts for platoons of vehicles arriving at the ramp meter. Required minimum storage lengths are as follows.

- One-lane ramp minimum queue length is 480 feet.
- Two-lane ramp minimum queue length is 480 feet per lane.
- Three-lane ramp minimum queue length is 510 feet per lane.

Minimum storage lengths are added to the calculated queue lengths so that the platooning of vehicles arriving at the ramp meter is accounted for.

In calculating required storage lengths, the number of HOVs is not deducted from the ramp demand because HOVs are metered even if an HOV bypass lane is provided.

For unconventional interchanges (e.g., diverging diamond interchange), additional analysis (such as simulation) is required to ensure that the calculated storage length is adequate.

Based on this approach, the following are two example calculations for storage length.

- **Example 1.** Calculate the required storage length for a ramp with projected peak hour volume of 1,790 vph.

  Step 1: Peak hour demand volume is 1,790 vph.

  Step 2: The 140-second arrival rate is 1,790 x 140/3600/0.8, which equals to 88 vehicles per cycle.

  Step 3: The required number of lanes is two lanes because the demand volume exceeds the one lane capacity of 800 vph.

  Step 4: Excess vehicles per 140-second cycle is 88 minus 62, which equals 26.

  Step 5: The total queue length is 26 x 30, which equals 780 feet.

  Step 6: The queue length per lane is 780/2, which equals 390 feet.

  Step 7: Calculated required storage length per lane is 480 (minimum queue length to account for platoons) plus 390, which equals **870 feet.**

- **Example 2.** Calculate required storage length for a ramp with projected peak hour volume of 580 vph.

  Step 1: Peak hour demand volume is 580 vph

  Step 2: The 140-second arrival rate is 580 x 140/3600/0.8, which equals 29 vehicles per cycle.

  Step 3: The required number of lanes is one lane because the demand volume is less than the one lane capacity of 800 vph.

  Step 4: For one lane ramps, the 140-second discharge rate is 31 vehicles. Because the discharge rate is greater than arrival rate, a minimum of **480 feet** of storage length is required.

2.11. Queue Management

The success of a ramp metering approach depends on the ability to smooth the flow of traffic onto the freeway, while adequately holding demand on the ramp. When demand exceeds the metering flow rate and storage on the ramp cannot handle the excess demand, traffic could back up to the adjacent arterial. This could disrupt operations on the adjacent arterial and other streets that feed into it. To mitigate these concerns, the following strategies can be used to manage queues.

- Available storage space is to be provided.[26]
- If sufficient space is not available, geometric changes are likely needed. This could involve widening the ramp to provide two or three lanes to expand the number of vehicles that can be stored.
- Modified metering rates could increase the flow on the ramp and reduce queuing. While this would negatively impact freeway operations, it prevents the queues from disrupting adjacent arterial operations.
- Signal timing revisions at the ramp terminal intersection could enhance storage capabilities by not allowing an influx of vehicles greater than the ramp storage capacity. Care must be taken to not cause significant delay.
- Providing additional storage on the adjacent arterial is an option. A portion of the adjacent arterial is used to store vehicles from the ramp queue. This requires retiming of traffic signals at nearby intersections to reduce the impact of the ramp queue on non-freeway bound traffic.
- A “two cars per green” scheme could be used with NDOT approval.

Most metering algorithms include a mechanism to increase metering rates when queues reach certain levels. This queue adjustment (or override feature) works only with traffic responsive control because it requires detectors to be placed on the ramp at locations that indicate critical queue lengths. If traffic backs up to these queue detectors, the metering rate is increased to keep the queue from getting longer. If a queue backs up to the adjacent arterial, oftentimes the queue is “flushed” (i.e., turning off the ramp meter temporarily to dissipate the queue).

Some traffic naturally diverts because of ramp metering and seeks routes without queues or meters. There are some ways to inform users of ramp delays so that they can make an informed choice. Where queuing is more severe, an active management approach addresses the queuing with signs upstream of the ramp that inform motorists of the traffic delay. For example, a DMS with the specific delay time (or the use of a simple blank-out sign) could be activated when the queues are unacceptable. Blank-out signs deployed on streets adjacent to the freeway help guide motorists to other, less congested ramps when severe queuing on the metered ramp occurs.

If there is no solution to reduce queuing that disrupts adjacent arterial traffic, then it may be decided to not meter the ramp. This decision is to be carefully evaluated because it could prevent an entire group of ramps from being metered.

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[26] See storage length calculations provided in Section 2.10.

2.12. Ramp Metering Operations

Ramp metering operations in the Las Vegas area is the responsibility of FAST on behalf of NDOT. Ramp metering operations in the Reno/Sparks area is the responsibility of NDOT.

2.12.1. Ramp Metering Turn-On Procedures

A ramp meter is to be analyzed and tested for problems and functionality before it is first turned-on to control live traffic. All system components (i.e., detectors, signals, controllers, and software/hardware) are to be tested.

Prior to turning on the meter(s), NDOT is to prepare answers to questions and concerns frequently posed by the public. Automated messages would extend to callers basic details pertaining to ramp metering. Messages could include a toll-free number for additional details via an operator or other information source. The public information number would be provided to other local and regional agencies, so these agencies can direct callers to the toll-free number. Approximately one week before ramp meters are implemented, signs indicating the date and time of metering would be placed on the prospective ramp(s) and along the mainline. Additionally, NDOT would contact the media to provide details of ramp metering operation. These actions serve as a final reminder to those that use ramps targeted for metering.[27]

FAST adheres to the following "ramp meter turn-on" procedure for ramp meters in the Las Vegas area.

- **Verify remote video monitoring.** As a minimum requirement, remote video monitoring capabilities at the FAST TMC are required prior to turn-on. This includes the capabilities to monitor the freeway flow immediately upstream and downstream of the ramp, the traffic behavior at the ramp meter stop bar, the queues on the ramp, and the queue backup to the adjacent arterial.
- **Verify on-line communications.** As a minimum requirement, the ramp meter controller must be on-line at the FAST TMC to allow remote upload and download, remote monitoring of controller functioning, collection of traffic data, and updating of clocks prior to turn-on.
- **Operations check and burn-in.** A complete operational check performed by FAST must be successfully completed prior to turn-on. A burn-in period of at least one week is required. During burn-in, the ramp meter operates with the police panel vehicle display switch in the "off" position. This ensures that all vehicle indications are dark. FAST performs the operations check during this time period and verifies proper operation of the controller, upload and download capabilities, and detectors. In addition, FAST staff that are responsible for operating each ramp meter field inspect and approve the signing, striping, and signal head configurations. If any item fails inspection, this burn-in period is extended at the discretion of NDOT and FAST.

In the Las Vegas area, ramp meters are an element of the FAST's Freeway Management System (FMS). The above procedure is applicable to other areas of Nevada where ramp meters are an

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[27] Additional detail on the appropriate and suggested media and public information activities prior to new ramp meter implementation is provided in Part 5: Public Outreach Primer.

element of FMS. In areas where FMS is not yet deployed (i.e., where ramp meters are used as a stand-alone congestion mitigation strategy) certain aspects of the above procedure (e.g., video monitoring and online communications) are not applicable.

2.12.2. Typical Ramp Meter Local Operation

NDOT selects a metering plan that achieves consistency in ramp meter operations. The plans are primarily designed to provide platoon dispersion and slightly spread the peak.

Multi-lane metering releases vehicles alternating between the lanes (a green light is shown to only one lane at a time.) Simultaneous green lights to multiple lanes are not currently permitted, except for the initial start-up for which a 5-second simultaneous green light is shown for all lanes.

The following summarizes the local operation of an NDOT ramp meter site when metering is active.

- Ramp meter signal commences “start-up” procedures to begin operation. Start-up procedures are as follows.
  - Advanced warning flasher is activated.
  - Simultaneous with the flasher activation, a green ball/light is displayed for all lanes for 5 seconds.
  - After the 5-second green display, a red ball/light is displayed for all lanes for 5 seconds.
  - Normal metering operation starts.
- Once the signal is in operation and if there are no vehicles present on the demand detector, the signal shows a red light until the maximum red time is reached.
- When a vehicle passes over the demand detector, a green light is displayed and the vehicle crosses the stop bar and travels over the passage detector. For multi-lane ramps, the green light is displayed only after the other lanes are served.[28]
- The green light is terminated, and a red light is displayed when the vehicle passes over the passage detector or when the maximum green time elapses.
- The signal remains red until the demand detector senses another vehicle (and other lanes are served) or until the maximum red time is reached.

The minimum and maximum times for green and red signal indications are user pre-selectable, and are typically set to the values shown in Table 2-6.

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[28] This does not occur immediately after a vehicle passes over the demand detector, instead that lane has to wait for its turn until the other lanes are served.

Table 2-6: Ramp Metering Parameters

Parameter	Typical Setting
Minimum Green	2 seconds
Maximum Green	5 seconds
Minimum Red	2 seconds
Maximum Red	30 seconds

If the controller recognizes a failure from the detectors, the controller switches the signal operation into pretimed mode in which a vehicle call is always made uniformly for each lane.

2.12.3. Ramp Metering Rates

For traffic responsive algorithms, which is the typical ramp metering practice, metering rates are determined based on the traffic conditions on the mainline within the immediate vicinity of the ramp. Rates are computed in real time to respond to current demand levels on the mainline using data from the mainline detectors. A queue override feature turns off the meter based on the presence of vehicles on the Advance Queue Detector (AQD). The purpose is to “flush” the queue.

For pretimed control, metering rates are determined based on historical traffic conditions at the ramp meter site.

Table 2-7 describes the different operating modes that NDOT ramp meters currently run.

Table 2-7: Ramp Metering Operating Modes

Operating Mode	Description
Manual	The user specifies the current operation of the meter manually from the front panel of the controller and from the TMC through the FMS software.
Local Traffic Responsive	The metering rate is selected by monitoring the speed and occupancy of traffic flow in the general-purpose lanes of the freeway mainline.
Local Pretimed	The meter operates at a fixed rate at the times and days specified by the user.

NDOT operates a majority of its ramp meters under “time of day/day of week” plans. These plans limit ramp meter operations to set time periods during morning and/or afternoon peak time periods throughout the week. Of these ramps, the majority operate under local traffic responsive mode, while the remainder operates under a local pretimed mode. NDOT and FAST are considering operating the ramp meters with central overview of intelligence with rates varying as a group rather than strictly based on local volumes as in the local traffic responsive mode. Communication with the FMS must be present for this “central override mode” (or “system-wide traffic responsive control”) to function.

For the Las Vegas area ramp meters that operate local traffic responsive, the metering rates are calculated based on the speed and occupancy of traffic flow in the general-purpose lanes of the freeway in the vicinity of the ramp. The meter selects a range of metering rates based on the average speed and occupancy in the general-purpose lanes. Metering rates range from 10 to 15 vehicles per minute for one-lane ramps, and 20 to 30 vehicles per minute for two-lane and three-lane ramps. Six uniform metering levels are used for each metering rate as shown in Table 2-8 and Table 2-9. The tables show metering rates and cycle lengths that correspond to each of these six metering levels.

Table 2-8: Ramp Metering Levels for 1-Lane Ramps

Metering Level	Rate (vehicle per minute)	Rate (vehicle per hour)	Cycle Length (seconds)
1	10	600	6.00
2	11	660	5.45
3	12	720	5.00
4	13	780	4.62
5	14	840	4.29
6	15	900	4.00

Table 2-9: Ramp Metering Levels for two-lane and three-lane Ramps

Metering Level	Rate (vehicle per minute)	Rate (vehicle per hour)	Cycle Length (seconds) (Two/Three lane)
1	20	1,200	6.00/9.00
2	22	1,320	5.45/8.18
3	24	1,440	5.00/7.50
4	26	1,560	4.62/6.92
5	28	1,680	4.29/6.43
6	30	1,800	4.00/6.00

Ramp metering starts at Metering Level 6 (least restrictive). The threshold for Metering Level 6 is 56 mph (i.e., when speeds are greater than 56 mph, the metering level is at Level 6). The metering rate is gradually decreased to Metering Level 1 (most restrictive) as freeway speeds drop. Threshold for Metering Level 1 is 22 mph (i.e., when speeds drop to 22 mph, Metering Level 1 initiates). Occupancy thresholds are 1 percent for Metering Level 6 and 35 percent for Metering Level 1.

2.12.4. Hours of Operation

Ramp meter operating hours are set by local operations staff in consultation with the NDOT Traffic Operations Division. Hours of operation are to be based on local traffic conditions and patterns.

Ramp meters operate only during peak periods throughout the initial operations period to reduce the probability of motorists' confusion and to confirm system predictability. Ramp meters are to be turned on/off at the same time everyday during the initial period of operation, unless otherwise indicated by the supervisor in charge of ramp metering operations. The initial period depends on several factors, including the degree to which motorists have adjusted to metering and the experience of the operators.

Ramp meters could operate outside the typical operation when emergencies occur or in unique situations where meter use benefits prevailing conditions. Ramp meters are to be turned on/off outside their normal hours of operation only by trained operators that are familiar with typical traffic patterns and problems.

2.12.5. Communications

Ideally, all ramp meter controllers would communicate to a central location. However, sometimes communication is not feasible because of the location of the ramps that are to be metered or when they are used for a temporary situation such as a special event or construction. Communications may also be too expensive or take too long to implement for the initial operation of the system.

In the Las Vegas area, FMS software allows FAST to monitor and control ramp metering from the FAST TMC. This also frees up operators to make adjustments to metering parameters in real time from a central location. This is the preferred communications approach. NDOT is currently planning a statewide FMS. Ramp metering operations for the Reno-Sparks metro area will be under the statewide FMS. When NDOT expands ramp metering statewide, all meters are expected to be an element of NDOT’s statewide FMS. An exception to this would be when metering is intended for special events, construction, or as an isolated stand-alone congestion mitigation strategy.

2.13. Resource Needs

Successful ramp metering requires that the appropriate resources be provided for specific activities that involve implementation, operation, and maintenance. Discussed in further detail below, funding is needed to:

- Acquire and deploy physical ramp meter components,
- Train and hire staff,
- Conduct public information and outreach activities,
- Provide enforcement,
- Perform ongoing maintenance,
- Monitor and report the performance of individual ramp meters, and
- Purchase the equipment and tools needed to keep meters operating as efficiently as possible (e.g., software, hardware, supplies, and vehicles).

2.13.1. Funding

Funding needs include typical capital project functions (i.e., planning, design, construction, administration, and the cost of the capital project) and operations costs that include staffing, training, and equipment maintenance. Funding levels and future funding needs in all the categories noted above must be identified prior to making decisions regarding deployment.

It is critical that cost estimates be included in budget development and capital programming activities. If the operations and maintenance costs cannot be budgeted, then the capital ramp metering projects are not to be included in the program.

Cost effective ways to leverage other funded projects are to be investigated. With adequate knowledge of the funding structure, there may be more than one way to fund additional ramp meters and support ramp metering.

2.13.2. Staffing

Before ramp meters are installed and/or turned on for the first time, existing staff skills and levels are reviewed to determine if additional staff needs to be hired, or if additional training is needed to successfully deploy, operate, and maintain ramp meters. Based on the results of this review and the anticipated funding levels, it would generally not be possible to effectively operate all the meters proposed for implementation. In these situations, ramp meters could be phased-in as funding levels permit, with existing staff to be trained or additional staff to be hired.

Ramp meters could be operated and maintained using staff employed by NDOT or a partner agency. If required, in-house staff can be supplemented by outsourcing. This approach is an option when it is difficult to fill technical positions that require high wages. It is often easier for a private firm to fill vacancies with appropriately-skilled personnel, as well as retrench poorly performing employees. Some of the problems with outsourcing include the necessity of continuing tight administration of performance under a contract, potentially higher turnover rates in contractor personnel than in-house staff, scarcity of private sector personnel with adequate experience, and friction of the contractor personnel with in-house staff. Outsourcing requires careful development of a detailed, clearly defined set of contractor requirements, which would entail task descriptions, schedules, performance standards, and payment terms.

2.13.3. Training

Depending on a review of staff knowledge, skills, and abilities (KSAs), in-house staff may need to be trained when new or additional ramp meters are installed. Training is categorized in two forms: technical and operational. Technical training covers how the equipment, communications network, and software work; and this type of training involves how to design, install, troubleshoot, and repair the system. Operational training is directed toward understanding the theories behind ramp metering and how to use ramp metering to achieve operational goals and objectives.

Numerous training programs are available through the National Highway Institute (NHI), Institute of Transportation Engineers (ITE), and American Society of Civil Engineers (ASCE). Training would include technical training (details of how the hardware and software work) that is often available through equipment and systems suppliers alongside functional concepts training (how to plan, design, operate, and maintain the system).

Identification of training needs is critical in the planning process because the process to identify qualifications and hire staff is time consuming. In addition, the needs are ongoing as agencies experience staff turnover and the system expands. To mitigate this issue, the training program would provide opportunities for training on an ongoing basis.

Training manuals are to be given to those who operate and maintain the ramp meters. Information on how to operate the system under various conditions can be incorporated into operating procedures. Training manuals are to include:

- Theories behind ramp metering,
- What type of adjustments are made based on performance,
- How to track ramp performance and associated measures of effectiveness, and
- How to use the existing tools in the TMC to monitor ramp performance.

The reason for including theoretical background information in the training manual is to tie together why ramp meters are being employed and what to expect under metering conditions. The operator has an opportunity to identify when ramp meters are producing the desired effect or when meters are not improving ramp performance.

The maintenance personnel training manual is to include at least a summary of the above information, in addition to detailed information on how the actual ramp metering equipment is to be maintained or replaced. These manuals would also include equipment manuals, installation and maintenance instructions, maintenance schedules, troubleshooting guides, and equipment vendor contacts.

2.14. Maintenance and Equipment

Maintenance personnel require the proper diagnostic equipment and tools to maintain individual ramp meters and the various associated components (e.g., detectors, signal, and controllers). Maintenance vehicles are to be available and equipped similarly to that of a traffic signal technician’s vehicle with the associated tools and replacement equipment. It is imperative that the hardware and software be kept up-to-date. Supply inventories are to be routinely re-stocked so maintenance activities can occur as needed or scheduled.

Staffing levels are to be commensurate with the number of devices implemented in the field. Although there are no guidelines on maintenance staffing, a study for the City of San Jose recommended 100 ITS devices (e.g., CCTV cameras, video detection units, DMSs, and ramp meters) per maintenance technician. This guideline is both reasonable and consistent with staffing levels at other agencies. It is recommended that a staff’s workload not exceed these levels to assure success for long-term operations.

Maintenance staff would also need diagnostic equipment to troubleshoot failures and maintain ramp metering equipment. FAST could be consulted regarding the typical equipment needed to maintain ramp metering systems.

Preventative maintenance periods and life cycle or replacement cycle for ramp controllers and other field equipment must be established.

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