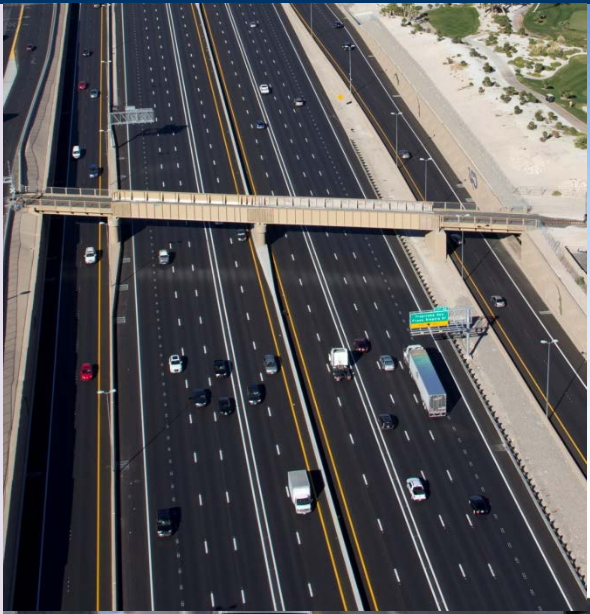
Managed Lanes and Ramp Metering Manual

Part 3: Design Manual



Prepared for:

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Part 3: Design Manual presents guidance on how to consistently design managed lanes and ramp meters throughout Nevada. Relevant background information and definitions are addressed in *Part 1: Introduction and Policies.*

1.0. MANAGED LANES DESIGN

1.1. General Design Controls and Considerations

Managed lanes design is to generally meet the requirements for urban freeway lanes specified in NDOT's *Road Design Guide* and the American Association of State Highway and Transportation Official's (AASHTO's) *A Policy on Geometric Design of Highways and Streets* (*AASHTO Green Book*). Access features and physical separation from the general-purpose lanes are the common design considerations that are unique to managed lanes. If pricing is part of the operation plan (or contemplated to be in the future), then additional design elements are to be considered.

1.1.1. Typical Vehicle Users

For High-Occupancy Vehicle (HOV) lanes, typical users are buses, carpools, vanpools, and motorcycles. Other types of managed lanes serve all types of vehicles, including trucks. Trucks are typically not allowed in HOV lanes; however, design of HOV lanes must account for truck use because they could be converted in the future to other types of managed lanes.

The turning radius of a bus is the most significant and unique design vehicle issue for managed lanes because this vehicle type has a wider turning radius. Turning requirements are particularly critical for direct-access ramps from transit facilities or local roads, or where turning at low speeds is required.

Within managed lanes, visibility is adversely affected in a single platoon of vehicles. Sight distance caused by a mix of higher and lower-profile vehicles could reduce vehicle headways and, thus, impact the lane's operating threshold. Because of typical median orientation of the lane, the horizontal separation (i.e., "shy" distance) to the median barrier, where full shoulders cannot otherwise be provided, could also adversely affect sight distance around curves. These are all considerations when designing managed lanes.

1.1.2. Operation Policy and Design

Operation policy is the basis for design selection and application. Operation policy must be easily understood and fully communicated to all motorists on signs, on pavement markings, and through the deployment of other traffic control devices. If the lane is open to all traffic during certain periods, the manner in which the lane is differentiated or physically separated must be clearly noted to avoid confusion outside the operating period. Of note, a consistent operation policy within a region promotes understanding and compliance, and could reduce the need for additional signing to explain the operation of the facility.

1.1.3. Managed Lane Orientation

Managed lanes are almost always oriented adjacent to the median (i.e., left side) to avoid conflicts with ramps from the right side and associated merging. Median orientations limit ingress and egress, and discourage users traveling short distances from using the managed lanes. Right-side managed lanes are appropriate in rare situations (see Section 1.4).

1.1.4. Design Exceptions or Variances

Feasibility of design could require design exceptions or variances. Often times, design exceptions occur when an existing roadway is modified to include managed lanes or to retrofit existing managed lanes. Exceptions may also be needed to avoid cost-prohibitive upgrades to substandard freeway sections that would undermine the feasibility of a managed lanes project. The application of each situation is often site-specific, and is for only a specified distance or timeframe. The design exception examples presented herein reflect each different contextual setting. The Federal Highway Administration's (FHWA's) *Design Exceptions Guide* provides further guidance related to design exceptions.

1.1.5. General Issues and Resolutions

The following are general design issues and resolutions that must be considered when designing managed lanes.

- **Consistency.** When addressing different operation policies (e.g., occupancy or hours of operation), the design must have consistent signs and pavement markings.
  - Use the same design criteria for successive projects.
  - Test sign messages on an initial project before repeating on successive projects.
  - Use previously successful sign messages.
- **Need for adequate lane balancing.** When two managed lanes merge, downstream demand could exceed a single lane's capacity. These forced merge conditions could cause queues that offset travel time savings and lead to bottlenecks that impact both safety and operational performance.
  - Carrying the commensurate number of lanes some distance downstream could effectively address the demand. Otherwise, a sufficient overall width is needed to allow for restriping to two lanes at obvious bottleneck locations where demand exceeds capacity.
  - Design is to be forward compatible for future connections and direct-access ramps.
- **Communication with different users.** Parallel facilities (i.e., managed and general-purpose lanes) located in constrained settings often make placement of motorist information difficult, and roadway signing guidance referenced in the FHWA's *Manual on Uniform Traffic Control Devices* (MUTCD) may not be entirely applicable in concentrated urban settings where mainline and ramps are not at current design standards.
  - Local tradeoffs are required to communicate information needs for the greatest number of users. A dynamic message sign (DMS) could alleviate such issues, but only if the sign addresses more than one user group and as dependent on the situation.[1]

[1] For example, a DMS located over a managed lane that normally provides occupancy or pricing information may have to serve a higher and better use by reporting a major accident ahead to all users.

- **Flexibility.** A common issue of managed lane design is not accounting for potential changes in operation policy. Many existing facilities throughout the country have modified occupancy requirements, hours of operation, access, and/or mainline design features over time.
  - Consider flexibility in managed lane design. Features that promote flexibility include:
    - Locating drainage inlets outside of the shoulders;
    - Providing wide clear zones around bridge columns;
    - Providing proper clear zones around gores;
    - Implementing a DMS or, minimally, conduit and fiber connectivity, where near-term potential exists to add pricing or access features;
    - Casting and placing barriers that are not integral to the pavement to better accommodate relocation;
    - Placing signs on common structures, even if the most optimal placement is compromised (subject to NDOT review);
    - Using markings that are easily altered in access zones until such time that operation confirms the length and location of the zone;
    - Providing shoulders on the mainline and ramps; and
    - Avoiding superelevation and other physical separation between managed and general-purpose lanes.

1.2. Lane and Roadway Geometrics

This section present typical cross-sections for the desirable and minimum designs for concurrent-flow, reversible-flow, and contraflow managed lanes. The priorities for accommodating key design features in constrained settings are provided through tradeoff tables that list an order for sequencing tradeoffs and cross-section design changes. Many candidate settings have bridge and related impediments that complicate the application of full design standards.

Desirable design is to be applied to all new and fully reconstructed roadways. Minimum design is to be used only for short distances, and when the constraints such as width, cost, and environmental impacts limit the application of a desirable design.

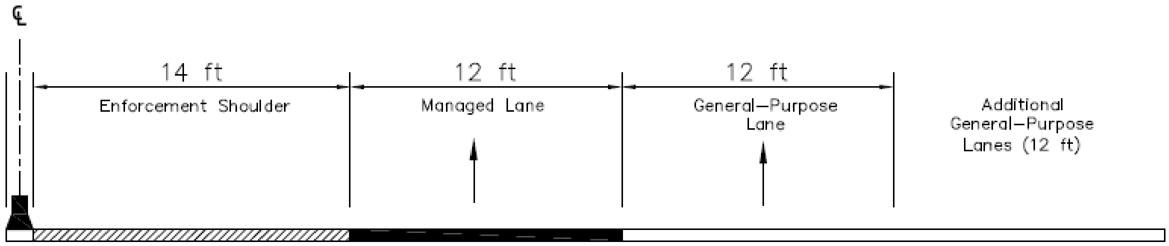
Because tradeoffs vary depending on site conditions, careful evaluation of the proper tradeoff for lane and shoulder widths is required. Tradeoffs include using minimum design (instead of desirable design) as well as some design exceptions.

When minimum design or tradeoffs are used, complementary operational treatments are to be incorporated.

1.2.1. Concurrent-Flow Lanes

Concurrent-flow lanes operate in the same travel direction as adjacent general-purpose lanes. These lanes could be physically separated from the general-purpose lanes with barriers, or they could be contiguous. Buffer separation is not a recommended option. Figure 1-1 and Figure 1-2 depict typical cross-sections for contiguous and barrier-separated concurrent-flow lanes respectively.

Figure 1-1: Contiguous Concurrent-Flow Lanes Typical Cross-Sections



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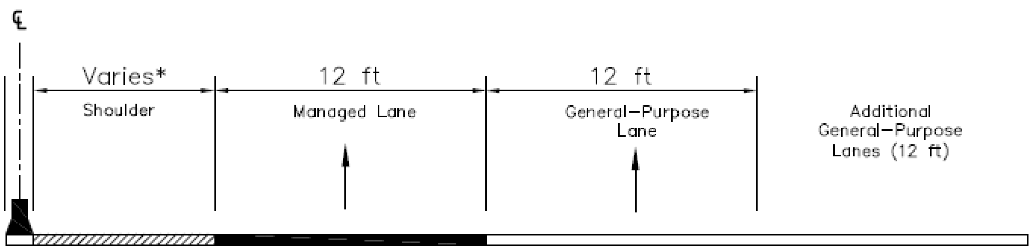
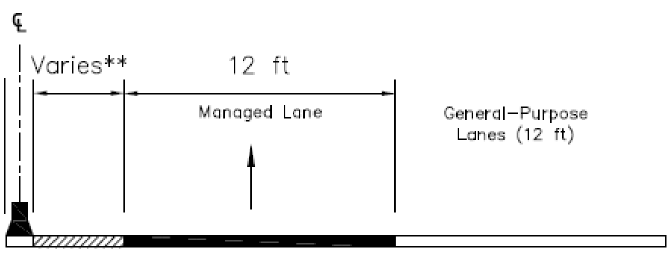


DESIRABLE



MINIMUM[1]

* Use "desirable criteria" from NDOT Standard Plans for Road and Bridge Construction.

** Use "minimum criteria" from NDOT Standard Plans for Road and Bridge Construction.

[1] Operational treatments are to be incorporated if the minimum design cross—section is used.

Figure 1-2: Barrier-Separated Concurrent-Flow Lanes Typical Cross-Sections

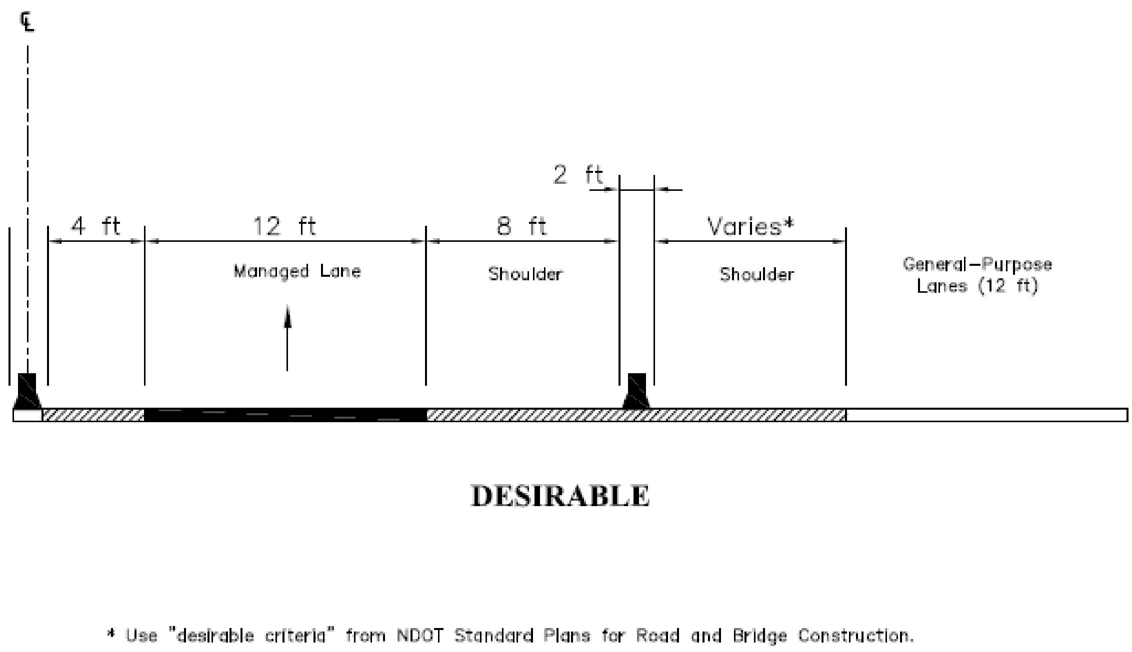


Table 1-1 and Table 1-2 provide potential tradeoffs for contiguous and barrier-separated concurrent-flow lanes respectively.

Table 1-1: Tradeoffs for Contiguous Concurrent-Flow Lanes

Suggested Sequence	Cross-Section Design Change
1	Reduce the 14-foot median shoulder (for continuous enforcement) to no less than the desirable criteria as per NDOT Standard Plans for Road and Bridge Construction (NDOT Standard Plans). Provide designated enforcement areas instead.
2	Reduce the median shoulder to the minimum criteria as per NDOT Standard Plans. This corresponds to the minimum design shown in Figure 1-1.
3	Reduce the outside (right) shoulder to a typical minimum width as per NDOT Standard Plans.
4	Reduce the median shoulder to 2 feet.*
5	Reduce the managed lane to 11 feet.*
6	Reduce the general-purpose lanes to 11 feet, starting from the left and moving to the right as needed. The outside (right) lane is to remain at 12 feet.*
7	Transition barrier shape at columns to vertical face.
*Requires design exception.	

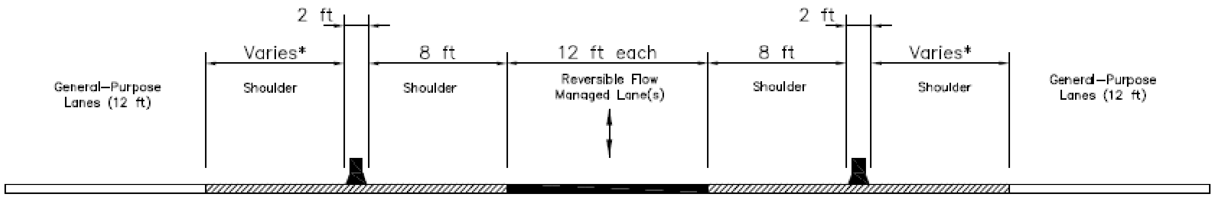
Table 1-2: Tradeoffs for Barrier-Separated Concurrent-Flow Lanes

Suggested Sequence	Cross-Section Design Change
1	Reduce the general-purpose lane left shoulder to the minimum criteria as per NDOT Standard Plans.
2	Reduce the outside (right) general-purpose lane shoulder to a typical minimum width as per NDOT Standard Plans.
3	Reduce the general-purpose lane left shoulder to 2 feet.*
4	Reduce the managed lane median (left) shoulder to 2 feet.*
5	Reduce the managed lane right shoulder to 6 feet.
6	Reduce the managed lane to 11 feet.*
7	Reduce the general-purpose lanes to 11 feet, starting from the left and moving to the right as needed. The outside (right) lane is to remain at 12 feet.*
8	Transition barrier shape at columns to vertical face.
Note: The width between two barriers must never be less than 20 feet. *Requires design exception.	

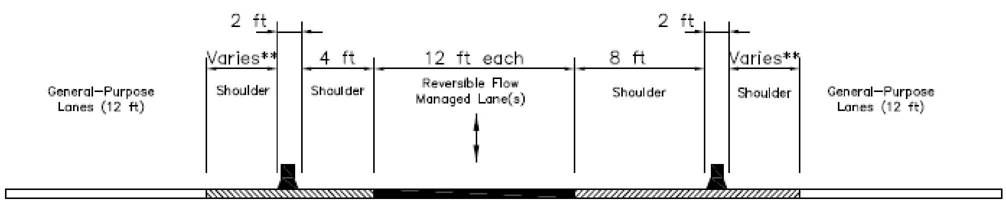
1.2.2. Reversible-Flow Lanes

Reversible-flow lanes operate in the median; are separated from adjacent, oncoming traffic by barriers; and accommodate single or multiple travel lanes. Figure 1-3 depicts typical cross-sections for reversible-flow lanes. Table 1-3 provides potential tradeoffs.

Figure 1-3: Reversible-Flow Lane Cross-Sections



DESIRABLE



MINIMUM[1]

* Use "desirable criteria" from NDOT Standard Plans for Road and Bridge Construction.

** Use "minimum criteria" from NDOT Standard Plans for Road and Bridge Construction.

[1] Operational treatments are to be incorporated if the minimum design cross–section is used.

Table 1-3: Tradeoffs for Reversible-Flow Lanes

Suggested Sequence	Cross-Section Design Change
1	Reduce the managed lanes shoulders to the minimum design shown in Figure 1-3.
2	Reduce the general-purpose lane left shoulder to minimum criteria as per NDOT Standard Plans. This corresponds to the minimum design shown in Figure 1-3.
3	Reduce the outside (right) general-purpose lanes shoulder to the typical minimum width as per NDOT Standard Plans.
4	Reduce the general-purpose lane left shoulder to 2 feet.*
5	Reduce the 4-foot managed lanes shoulder to 2 feet.
6	Reduce the 8-foot managed lanes shoulder to 6 feet.
7	Reduce the managed lane to 11 feet.*
8	Reduce the general-purpose lanes to 11 feet, starting from left and moving to the right as needed. The outside (right) lane is to remain at 12 feet.*
9	Transition barrier shape at columns to vertical face.
Note: The width between two barriers must never be less than 20 feet. *Requires design exception.	

1.2.3. Contraflow Lanes

Contraflow lanes borrow a lane from the off-peak direction for peak direction use by orienting traffic in opposing directions on the same side of the roadway. Moveable barriers are used to separate the traffic. The AASHTO's *Guide for High-Occupancy Vehicles* provides examples of cross-sections for contraflow lanes.

1.3. Access Design

Access design involves both how a lane transitions to and from adjacent general-purpose lanes (i.e., beginning and termination) and the extent of intermediate access treatments. Lighting must be provided at each access location as per typical freeway lighting criteria in the NDOT Standard Plans.

Concurrent-flow lanes. Concurrent-flow lanes could have continuous access or limited access. For limited-access facilities, designated at-grade intermediate access zones (Section 1.3.2) or direct-access ramps (Section 1.3.3) are used.

Reversible-flow lanes: For reversible-flow lanes, any at-grade access must be channelized through separation barriers with proper gating and signs (Figure 1-4). Otherwise, access must be grade-separated over the general-purpose lanes (Section 1.3.3). Typical access features for reversible-flow lanes include the following features.

- There is single-lane channelization with barriers to guide traffic into and out of the reversible roadway.
- A series of breakaway gate arms followed by a solid moveable barrier at each high-speed entrance prevent wrong-way movements when the gate is closed.

- A DMS or mechanical sign (at least one in advance and one at the entrance) indicates if the entrance is open or closed.
- Lane control signs assist in communicating lane operating status.
- Other traffic control devices (e.g., delineators or DMSs) reinforce ramp operating status.

Figure 1-4: Channelized Access for Reversible-Flow Lanes

Contraflow lanes: Access to contraflow lanes is usually provided by clearly signed, at-grade median crossovers.

1.3.1. Beginning and Termination

Design for both beginning and termination treatment locations must consider proximity to existing or planned ramps from the right side. A minimum of 800 feet "per-lane change distance" must be provided between the ramps and the beginning/termination of the managed lanes (Figure 1-11_C in Section 1.3.2). The specific distance is to be determined based on a weaving analysis, and designers are encouraged to provide distances greater than the minimum where possible.

1.3.1.1. Beginning a Managed Lane

Since a majority of managed lanes are located on the left, the beginning of a managed lane is not to cause general traffic to drive into a downstream restricted condition. It is recommended that managed lanes be added to the overall roadway cross-section using a standard left-side lane addition (Figure 1-5).

1.3.1.2. Terminating a Managed Lane

Managed lanes that otherwise save time should not cause users to lose time where they terminate and merge into the general-purpose lanes. Dependant largely on anticipated volumes, downstream termination must be designed to merge traffic into other lanes (Figure 1-6). If demand is high (typically over 1,000 vehicles per hour [vph]), it is preferred that the managed lane continues as a general-purpose lane, with an outside general-purpose lane dropped further downstream. As an option, the outside general-purpose lane can be dropped at an exit ramp (Figure 1-7). Termination treatment is to be determined based on a traffic operational analysis.

The design of the terminus location is to consider grade, curvature, and traffic conditions specific to the project. Tangent locations are encouraged where good sight distances exist.

Figure 1-5: Beginning a Managed Lane

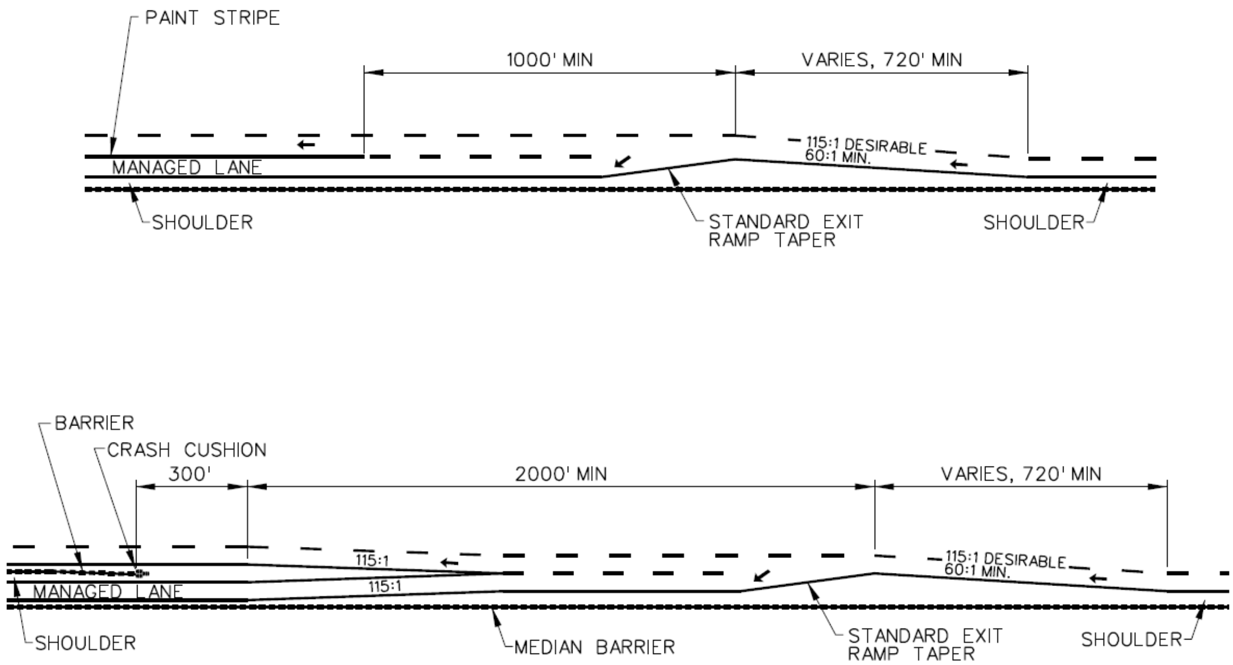


Figure 1-6: Terminating a Managed Lane

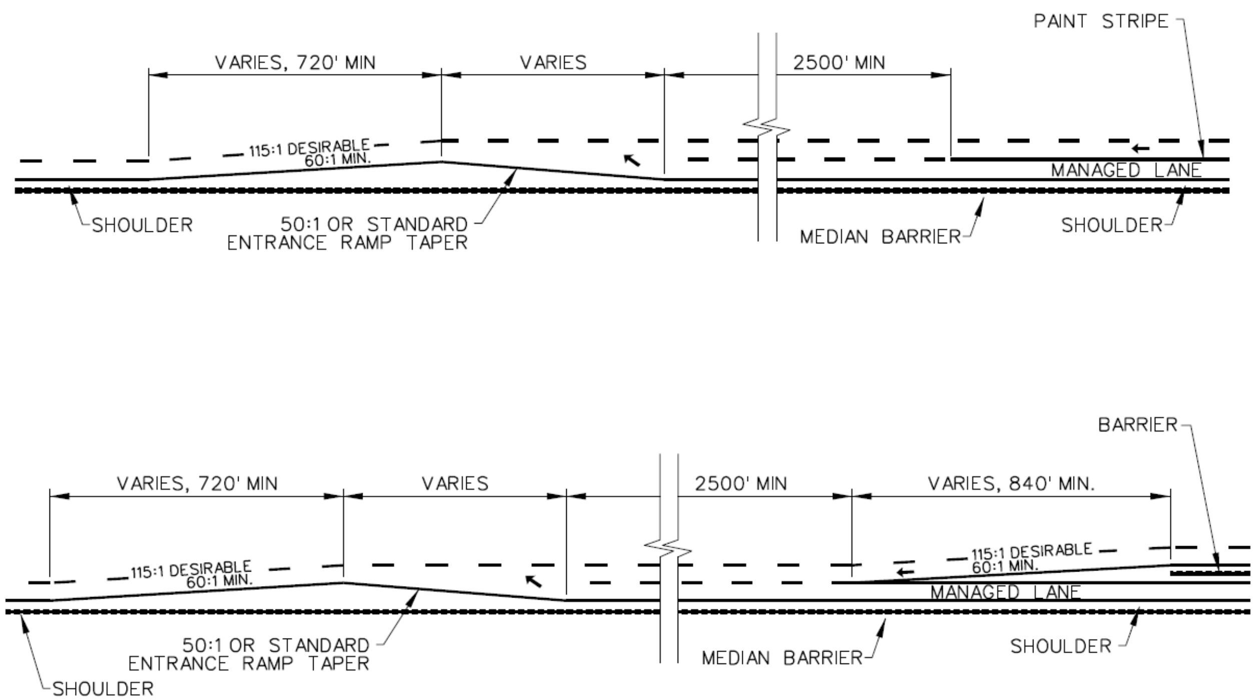
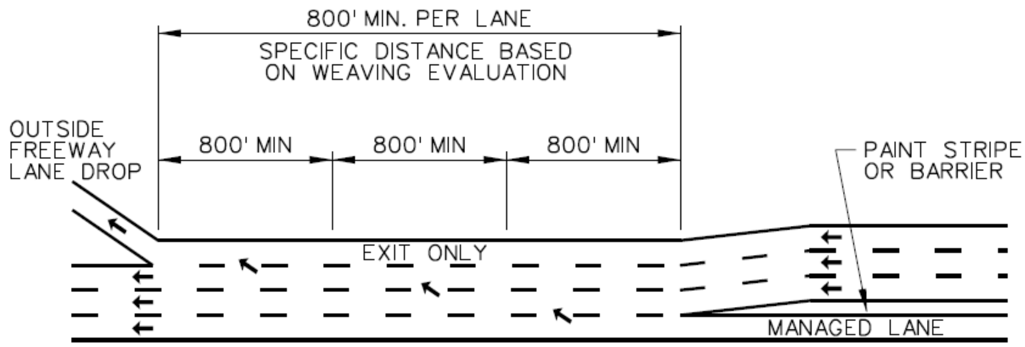


Figure 1-7: Terminating a Managed Lane as a General-Purpose Lane

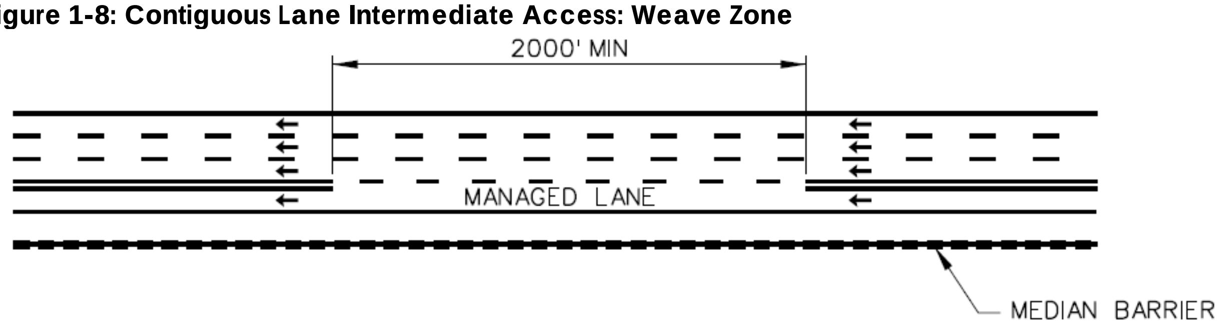


1.3.2. At-Grade Intermediate Access

Types, locations, and opening length of access locations on limited-access, concurrent-flow lanes are to be based on a traffic operational analysis. There are three at-grade intermediate access options for limited-access, concurrent-flow lanes.

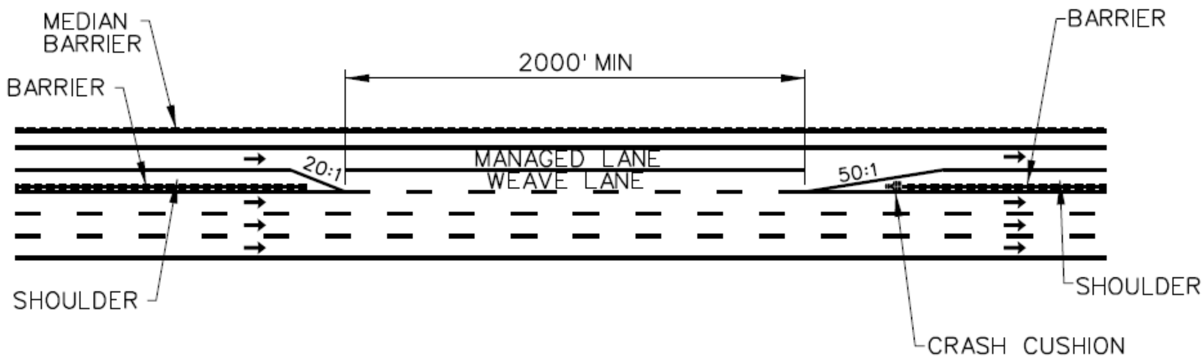
Weave Zones: Simultaneous Ingress/Egress. Weave zones are designed as breaks in the striping to allow simultaneous ingress and egress. This is the most common form of at-grade access on limited-access, concurrent-flow lanes. The length of the access zone must be a minimum of 2,000 feet (Figure 1-8).

Figure 1-8: Contiguous Lane Intermediate Access: Weave Zone



Weave Lanes: Simultaneous Ingress/Egress. This option is similar to a weave zone except that the ingress/egress is facilitated by a weave lane to account for the speed differential between the managed and general-purpose lanes. The length of the access weave lane must be a minimum of 2,000 feet. Weave lanes are desirable on contiguous lanes if high-access volumes or multiple managed lanes exist. For barrier-separated lanes, if the ingress/egress is simultaneous, a weave lane is always required (Figure 1-9).

Figure 1-9: Barrier-Separated Lane Intermediate Access: Weave Lane



Slip Lanes: Separate Ingress/Egress. When high-access volumes or multiple managed lanes are anticipated, another option is to separate ingress and egress. When separated, intermediate access occurs through dedicated acceleration and deceleration lanes (i.e., slip lanes). The length of the access zone must be a minimum of 1,000 feet (Figure 1-10).

Figure 1-10: Separate Ingress/Egress Lanes

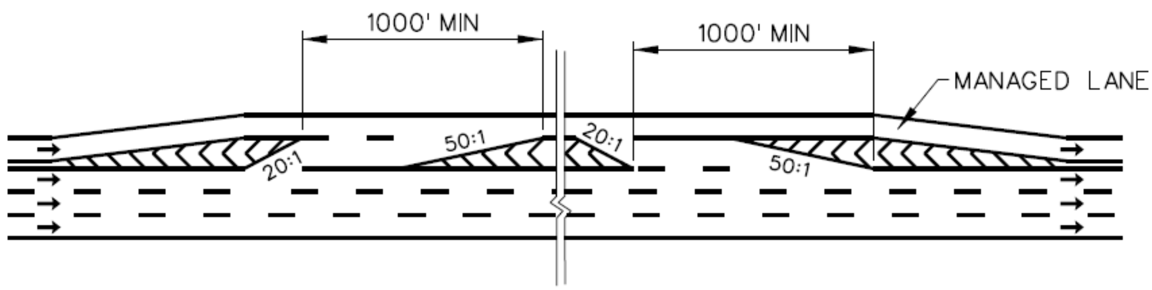
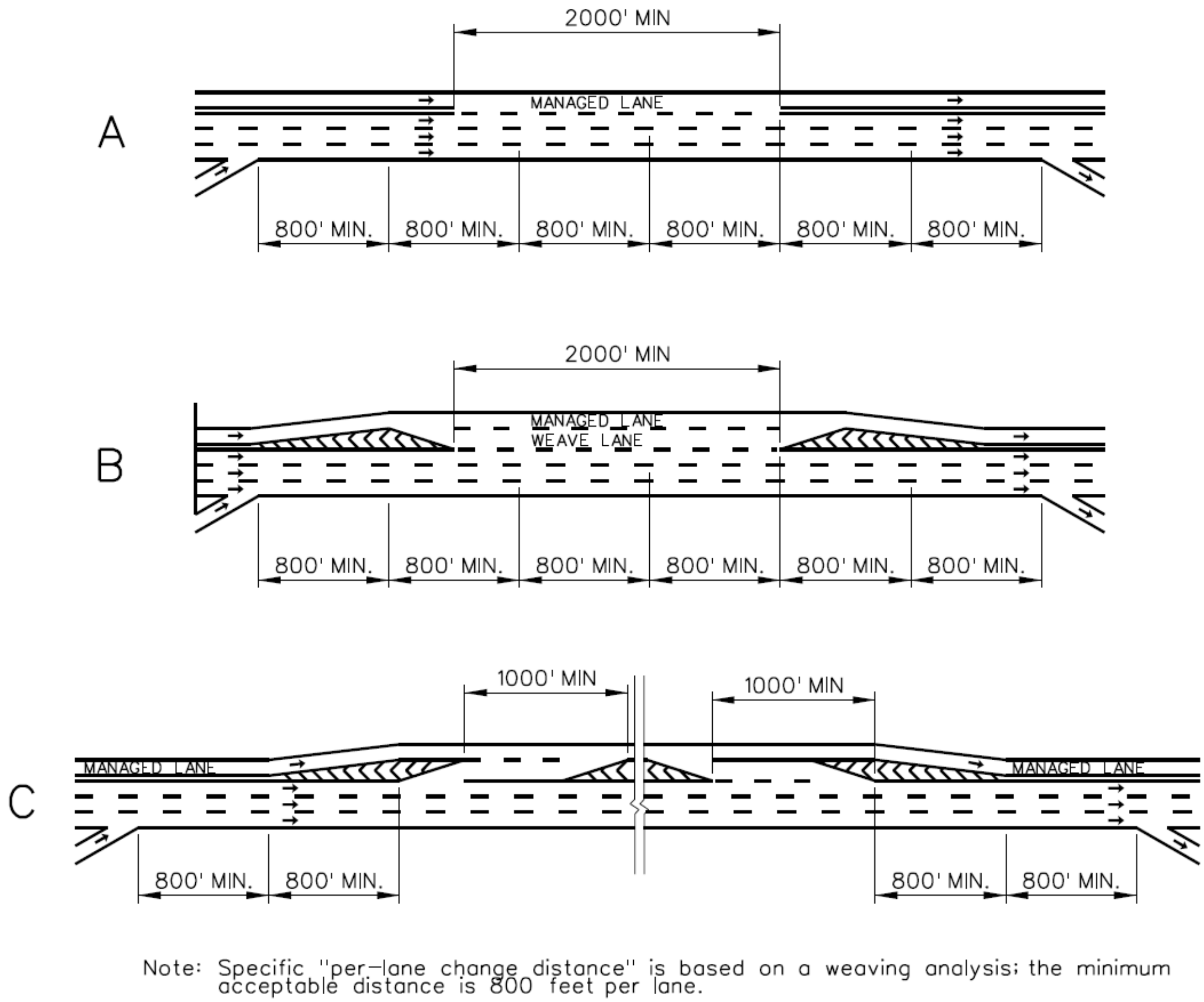


Figure 1-11 illustrates the "per-lane change distance" between at-grade access and the ramps.

Figure 1-11: Per-Lane Change Distance



1.3.3. Direct-Access

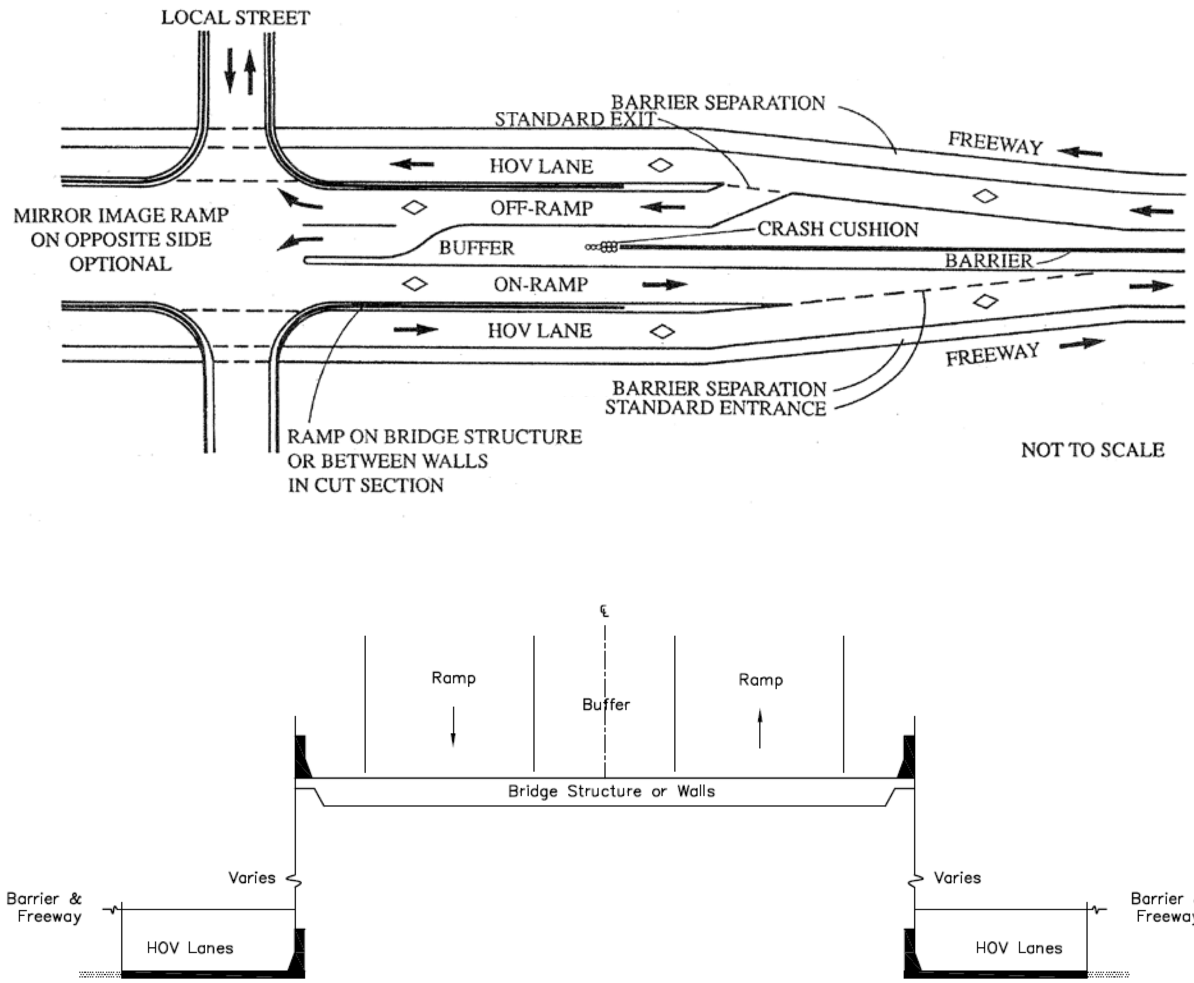
Grade-separated, direct-access ramps could be more appropriate for high traffic volumes where weaving problems are anticipated and where high demand for managed lanes exists.

1.3.3.1. Direct-Access Local Drop Ramps

Direct-access local drop ramps (also referred to as T-ramps) are configured within the median with left-side entrance and exit ramps to the managed lanes. These ramps can be oriented in one or both freeway directions. Drop ramps require careful design that accounts for the sight distance that lead traffic from high-speed to low-speed conditions (or vice-versa) in a short distance.

Drop ramps to concurrent-flow lanes are typically two-way, with a barrier that transitions to an open buffer or curb section between opposing directions. Figure 1-12 depicts an example layout for drop ramps to concurrent flow lanes. [2]

Figure 1-12: Example Layout for a Two-Way Drop Ramp to Concurrent-Flow Lanes



Reversible-flow lanes could also involve drop ramps located to the left or right side of the reversible roadway (Figure 1-13).[3]

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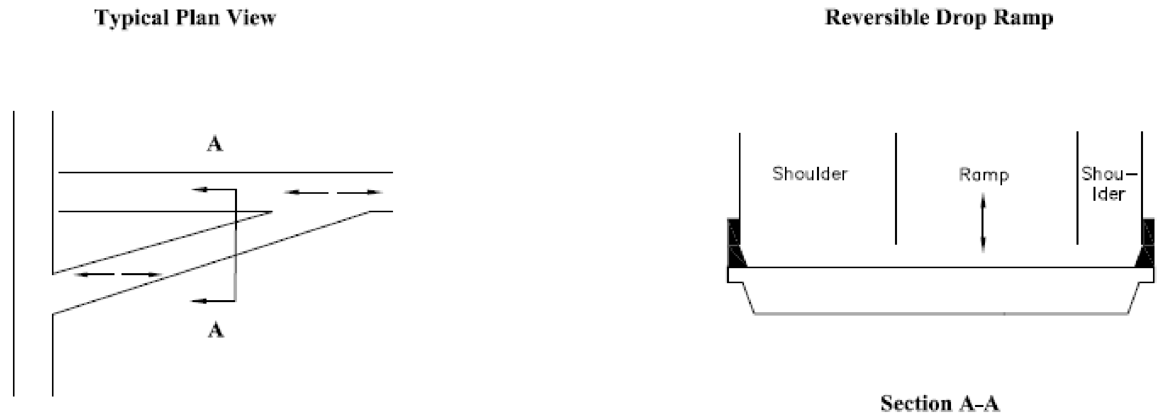
[2] The Texas Transportation Institute's (TTI's) *Managed Lanes Handbook* provides several examples of additional layout options for direct-access local drop ramps.

[3] Notably, the most significant safety issue with a reversible-flow drop ramp is gating and signing the roadway such that the design addresses potential wrong-way movements. Two strategies for eliminating this issue involve channelizing the ramp terminus with gating to remove the likelihood of wrong-way movements or installing a gate that is traffic-actuated.

Figure 1-13: Example Layout for a Reversible Drop Ramp



1.3.3.2. Direct-Access Flyover Ramps

Direct-access flyover ramps (also referred to as direct connectors) are designed to have the same geometric and design speed conditions as any other high-speed, freeway-to-freeway connector. By sharing a common structure, these ramps are most commonly oriented to the left of the mainline managed lane and are connected left to left (Figure 1-14). The cross-section for a direct-access flyover ramp is the same as a two-way, barrier-separated managed lane shown in Figure 1-2.

Direct-access flyover ramps typically serve selected high-volume movements within an all-directional interchange. Where demand exists for multiple movements, a median-oriented ramp could be attached to the existing freeway interchange connectors (Figure 1-15). In each case, the ability to provide safe merging and weaving distances and appropriate signing is critical when considering direct-access flyover ramps.

High-volume, direct-access ramps between intersecting managed lanes could require carrying an added lane a distance before it can be merged or dropped. Forced merges within single managed lanes are to be avoided unless anticipated volumes are low. A separate merge section that allows vehicles to smoothly transition into the managed lanes could be used for these circumstances.

Direct connectors are also a means to terminating managed lanes. Specifically for reversible-flow lanes, this approach allows better gating and control of traffic from the right side, while allowing access to major freeway ramps for better distribution of traffic, which reduces weaving.[4]

[4] TTI's *Managed Lanes Handbook* provides several examples for additional layout options for direct connectors.

Figure 1-14: Example Layout for a Freeway-to-Freeway HOV Direct Connector

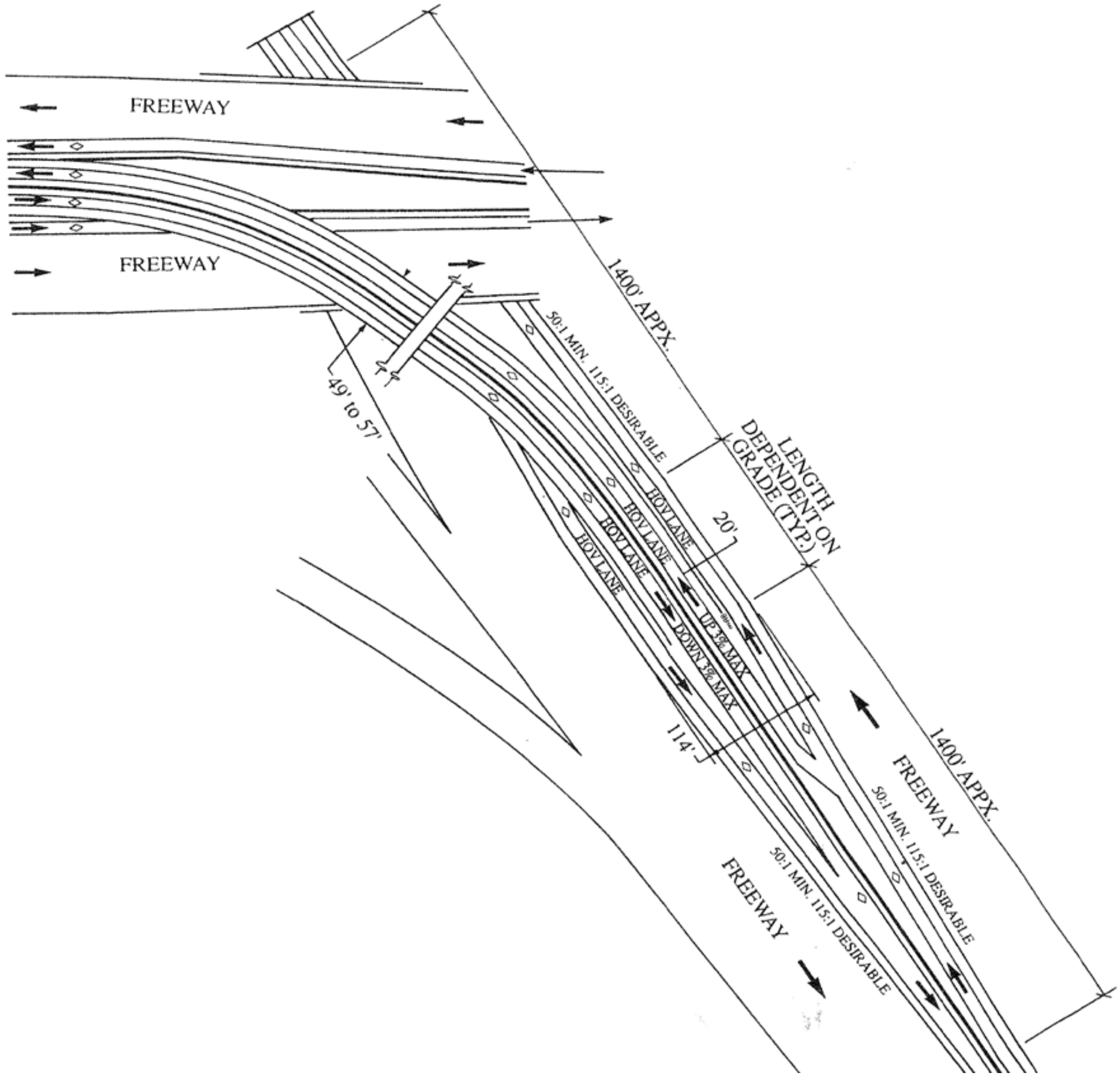
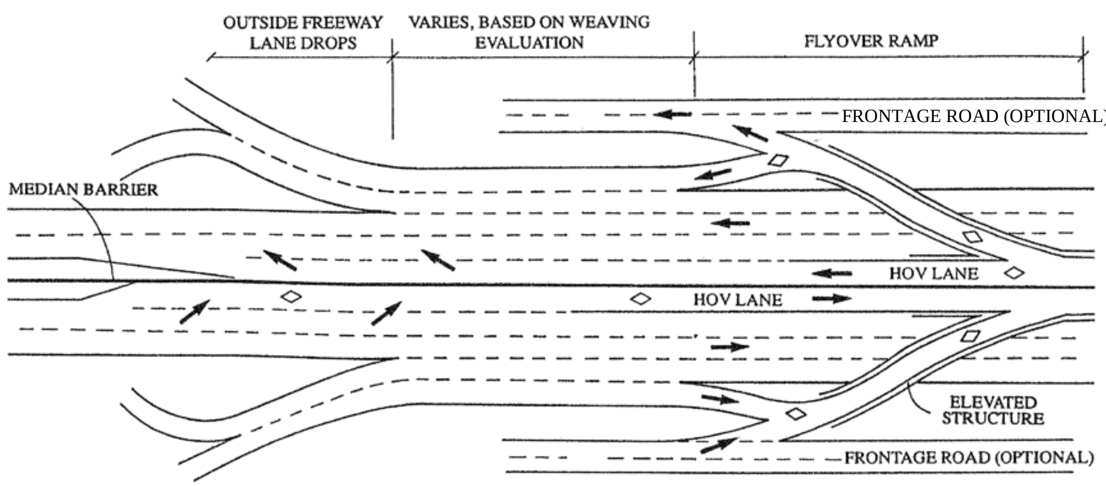


Figure 1-15: Example Layout for a Direct Connector to Existing Interchange



1.4. Right-Side Oriented Managed Lanes

Managed lanes are typically oriented adjacent to the median. Where bus routings either use a freeway for a short distance or where transit stations and stops are located along the freeway, a right-side (or shoulder) bus lane might be appropriate. There are only a few applications of a right-side bus lane on freeways, and operational experience suggests that this type of orientation works best when both the bus volumes as well as the entering and exiting volumes on the freeway are quite low. The right-side option may work for carpools if the occupancy requirements are set at HOV 3+ so that demand does not cause conflicts with entrance and exit ramps. Figure 1-16 is an example of a right-side HOV lane operating on the shoulder.

Figure 1-16: Right-Side HOV Lanes Operated on Shoulder

When using the shoulder as a travel lane, the design of adjacent roadway elements must also be contemplated.[5] Some roadway elements may necessitate modification in order to accommodate regularly occurring traffic, particularly if the intent is to permit buses. The design and traffic control devices must also allow for interaction of other vehicles at entrance and exit ramps.

Outside-shoulder dedicated lane treatments on freeways are not suitable for a heavy volume of mixed buses and carpools. However, such treatments can be applicable for short distances to serve as a bus queue bypass between successive local access ramps and for temporary settings where transit stops already exist. Outside shoulder use is to be clearly signed. Speeds are to be reduced for shoulder users, and all conditions are to be closely monitored.[6]

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[5] Examples of roadway elements include vertical clearance to overpasses, horizontal clearance to roadside objects (e.g., guardrails and culverts), and the shoulder (e.g., width, pavement and sub-base design, vaults, and drainage).

[6] The Transportation Research Board's (TRB's) *Transit Cooperative Research Program (TCRP) Synthesis* 64 *Bus Use of Shoulders* and AASHTO's *Guide for Geometric Design of Transit Facilities on Highways and Streets* are useful resources on this subject.

1.5. Enforcement Area Design

One of the most critical elements to managed lane enforcement is providing safe and convenient enforcement areas throughout a freeway. If a continuous enforcement shoulder cannot be provided, then designated enforcement areas are necessary. Even with automated enforcement for toll facilities, on-site enforcement is still suggested.[7]

It is recommended that all enforcement requirements be coordinated with the enforcing agency as early in the design process as feasible. This allows law enforcement personnel to become familiar with the project; to anticipate any additional requirements or revisions to the initial concepts; and to offer suggestions for the design that could ensure enforcement is safer, more efficient, and compliant with local laws.

The primary type of infraction that enforcement officers confront is occupancy violations, which requires the officer to see inside a vehicle and count the number of occupants. Good lighting and a safe vantage point are needed to perform these enforcement functions.

Table 1-4 highlights some of the attributes associated with managed lane enforcement strategies that have been successful.

Table 1-4: Enforcement Attributes for Different Managed Lane Facilities

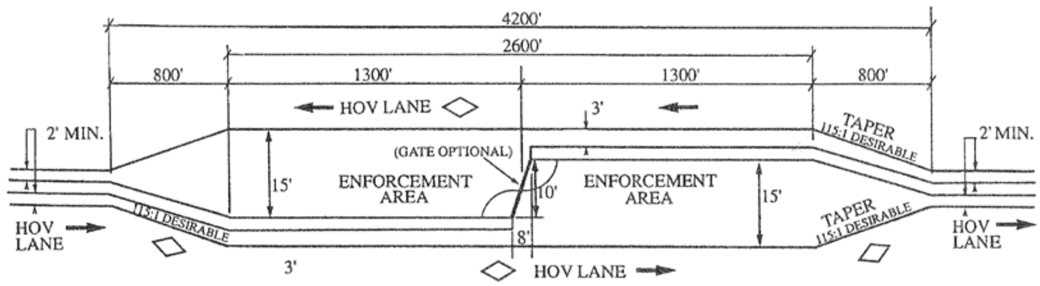
Type of Facility	*Preferred Enforcement Attributes*	*Minimum Enforcement Attributes*
Barrier Separated Lanes: Concurrent-Flow and Reversible-Flow	♦ Enforcement areas at access points (i.e., entrances and exits)	♦ Enforcement areas at entrances or exits
Contiguous Lanes: Concurrent-Flow	♦ Continuous enforcement shoulders	♦ Periodic mainline enforcement areas ♦ Continuous left-side shoulders
Contraflow Lanes	♦ Continuous enforcement shoulders	♦ Enforcement area at entrance
Note: Barrier-separated lanes are generally easier to enforce than contiguous lanes because of the controlled-access features.		

For concurrent-flow lanes, Figure 1-17 and Figure 1-18 illustrate a typical layout for a median enforcement area. Law enforcement personnel could monitor traffic by parking in the enforcement area and accelerating to enter the lane and enforce further downstream, or park and wave violators over into the median enforcement area. The layout length is to allow violators to be stopped, and then accelerate and merge safely back into traffic.

[7] Current technologies cannot accurately discern the number of occupants in vehicles traveling at freeway speeds. The presence of on-site enforcement is also a deterrent to violators.

Figure 1-17: Median Enforcement Area Layouts

Typical Layout without Inside Shoulders



Typical Layout with Inside Shoulders

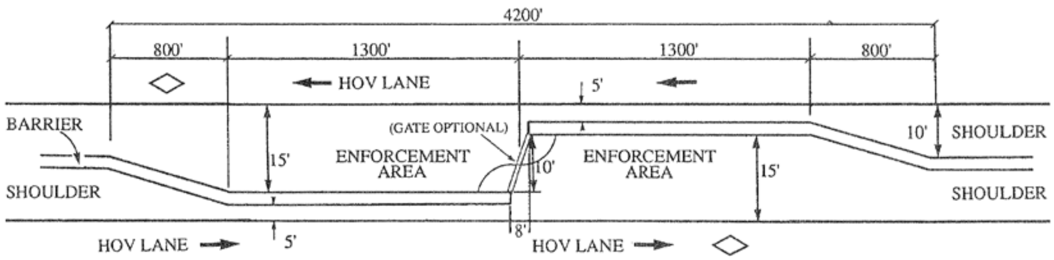


Figure 1-18: Examples of Median Enforcement Areas

Enforcement areas are to be flexible to address a variety of enforcement strategies; and while there are no prescribed layouts, good sight distance, suitable locations, and illumination are important considerations. On barrier-separated facilities, enforcement actions can be performed near the entrance or exit ramps where traffic is often moving more slowly (Figure 1-19). If located near a slow-speed entrance or exit ramp, design could include a designated parking pad on one side of the ramp (or in the unused portion of the ramp for reversible-flow conditions).

Enforcement could occur anywhere if a continuous enforcement shoulder is provided, which offers more flexibility for enforcement activities (Figure 1-20). In more restrictive settings, enforcement areas allow officers to monitor traffic, with citation issuing at a downstream location. This location may be another enforcement area or a wide left or right shoulder.

Figure 1-19: Potential Locations for Low-Speed Enforcement Areas

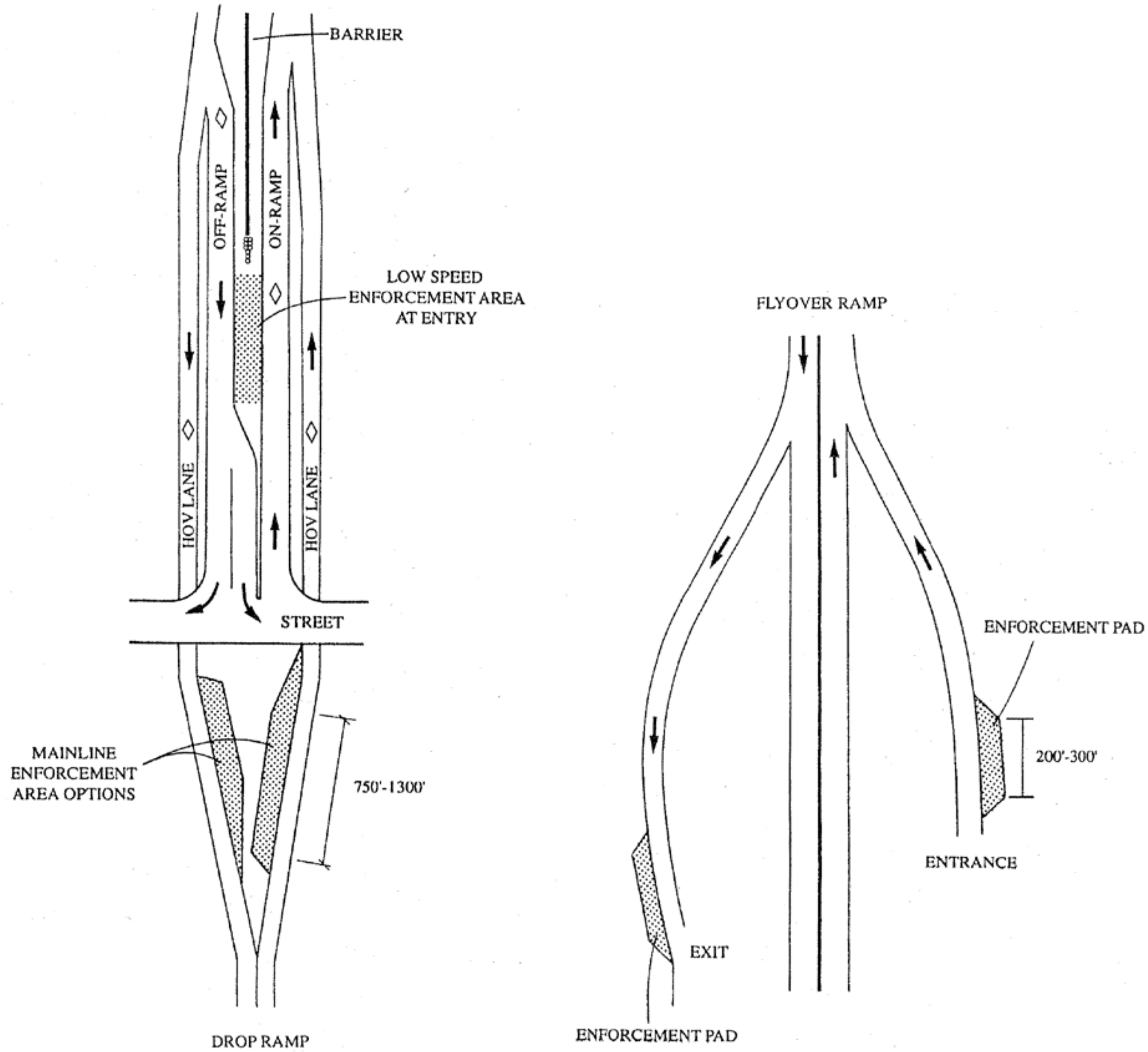
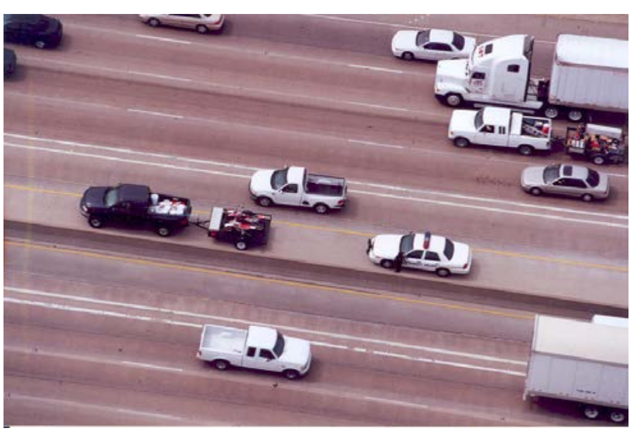


Figure 1-20: Enforcement Area: Shoulder



1.6. Pavement Markings and Signs

Pavement markings and signs for managed lanes must conform to guidance provided in the most recent editions of the MUTCD, NDOT Standard Plans, and Nevada Sign Supplement.

1.6.1. Pavement Markings

Key design features for pavement markings are as follows.

- For contiguous lanes, lane line markings separating the managed lane(s) from the general-purpose lanes must be 8 inches wide. The 8-inch criterion applies to both single and double white lane lines.
- The standard pavement marking for HOV lanes is a diamond symbol at regular intervals.
- The regular spacing of markings (e.g., HOV diamond symbol and word markings for managed lanes) are to be approximately every quarter mile. In addition to regular spacing, the markings are to be placed at strategic locations (e.g., major decision points) and along access openings to and from adjacent general-purpose lanes.

1.6.2. Signs

Key design features for signs are as follows.

- The diamond symbol is reserved exclusively for HOV lanes and is not to be used to designate a managed lane with other operational strategies. Posting of advisory and regulatory conditions is to be on a sign panel with a diamond in the upper left. This ensures that the sign communicates only to the HOV lane users.
- Signs are to be designed and located to avoid overloading the freeway user. Regulatory signs are given priority over guide signs.
- For HOV lanes, regulatory signs related to occupancy requirements and hours of operation must be posted at frequent intervals. Regulatory information can be ground mounted on the median barrier. Aside from occupancy and operation restrictions, other applications of regulatory signs could include allowance for motorcycles, exclusion of trucks, lane line crossing, and emergency shoulder use.
- Barrier-separated lanes must include more overhead-mounted signs, particularly at designated access locations. Contiguous lanes could apply median barrier-mounted signs. It is not recommended that pricing signs be located at the access point in order to discourage last minute decision making.
- There are many challenges for managed lanes signing in which operational strategies are employed that allow general-purpose traffic to use the lane. Because of the dynamic nature of an operation that may change hour by hour with different pricing, eligibility, and access controls, sign design must account for an array of operational possibilities, some of which may not be determined or known on opening day. Design flexibility is critical to providing the greatest potential for controlling managed lanes through typical demand conditions, as well as special events and incidents. These circumstances suggest that updated information is likely to be communicated through the use of DMSs. DMS elements to static signs could be used, or for ultimate flexibility, the entire panel would

be dynamic. Messages on managed lane signs are to be presented such that the number of lines a driver needs to read are minimized.

- Guide signs for managed lanes must follow standard freeway guide signing criteria, with emphasis on the need for redundancy and advance access information. If access to the lanes is restricted, guide signs are to be mounted overhead to the extent possible. Exit destination supplemental guide signs that identify final destination and downstream exit locations accessible from the managed lanes are to be installed in advance of the initial entry points. The exit destination signs are to be located based on the priority of the message, the available space, the existing signs on the adjacent general-purpose lanes, roadway characteristics, the proximity to existing overhead signs, the ability to install overhead signs, and other unique factors. Exit destination signs generally consist of two or three lines with names of significant destination points and distances to those points. Consistency is key in implementing these types of signs.
- Where possible, regulatory and guidance information could be combined on the same sign structure or panel.[8] This condition is most applicable at access locations where managed lane signs on the left side would compete with general-purpose ramp exit signs on the right side.
- General-purpose route names are to be used in conjunction with the legend of the managed lanes (e.g., EXPRESS LANES) to reassure users that the managed lanes remain adjacent to the general-purpose lanes.

1.7. Support Facilities

The two most common support facilities for managed lanes are transit stations and parking facilities. AASHTO's *Guide for Geometric Design of Transit Facilities on Highways and Streets* should be consulted for design of transit stations. Parking facilities are addressed below.

1.8. Park-and-Ride and Park-and-Pool Lots

Park-and-ride and park-and-pool lots are parking lots created for users who gather in a central location to either access transit (i.e., park-and-ride lots) or carpool with others (i.e., park-and-pool lots). Larger lots intended for regularly scheduled transit service are often park-and-ride lots, although carpooling could also occur at park-and-ride lots.[9]

Park-and-ride lots are typically 500- to 1,000-space facilities typically located 5 to 8 miles from major employment centers. These lots are serviced by express transit routes and are sized to serve commuters from major residential markets. Park-and-ride lots are best located within a quarter mile from a freeway with good access for transit to the HOV lanes. Drop ramps (Figure 1-21) or flyover ramps (Figure 1-22) could be designed into the lots if the ramps are within proximity to the freeway. Separating bus access from parking users improves traffic flow and transit service reliability.

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[8] Some elements of the sign could be fixed while some are dynamic.

9 AASHTO's *Guide for Park and Ride Facilities* provides design guidance for park-and-ride and park-and-pool lots, and design of these facilities is to conform to this guide.

Figure 1-21: A Park-and-Ride Lot with Drop Ramps

Figure 1-22: A Park-and-Ride Lot with a Flyover Ramp

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2.0. RAMP METER DESIGN

2.1. Ramp Metering Design Considerations

The primary design considerations for ramp metering are the required number of lanes, meter and stop bar location, enforcement area provision, and acceleration length. The following sections describe these design considerations. Figure 2-1 depicts a general layout of the various ramp metering elements.

2.1.1. Number of Lanes

The required number of lanes on a metered ramp is based on the ramp peak hour volume demand, required queue storage, ramp meter release rate, and available ramp width.[10] Available ramp width could be based on the existing ramp width or the width feasible based on geometrics and topography.

An HOV bypass lane is to be provided at every urban ramp where ramp metering is installed (see Section 2.2 for tradeoffs). The left side of the ramp is the typical HOV bypass lane location. A right-side HOV bypass lane could be approved when adequately justified and at the sole discretion of NDOT.

2.1.2. Meter and Stop Bar Location

The location of a ramp meter and stop bar must strike a balance between available ramp queue storage space and the acceleration distance to the freeway. The ramp meter and stop bar must be located at a position on the ramp that allows vehicles enough distance to accelerate to freeway speeds and merge safely with freeway traffic. A stop bar's location is to be a minimum of 75 feet upstream of the physical gore.[11]

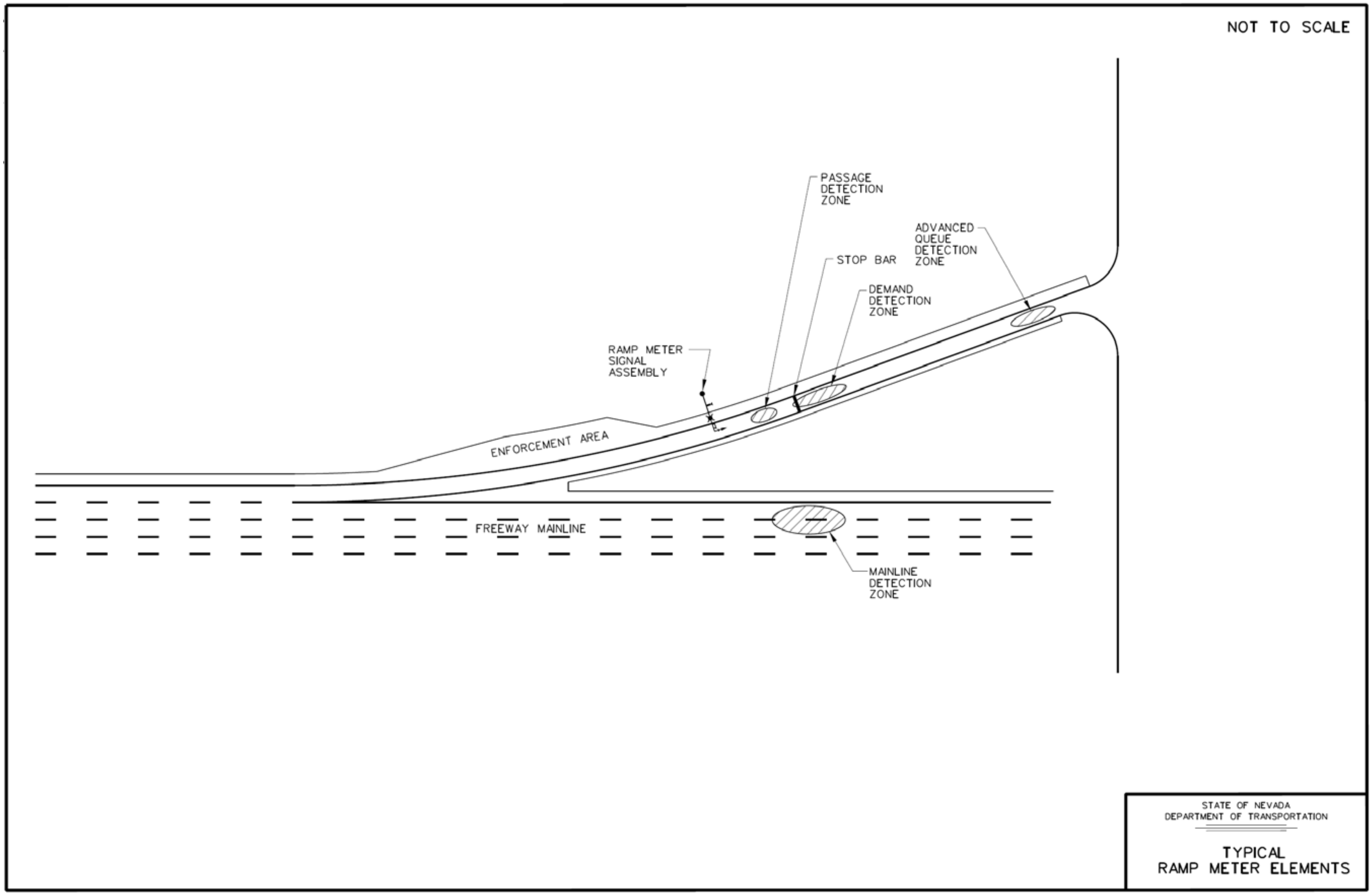
Locating the ramp meter and stop bar further down the ramp maximizes the available storage space on a ramp. This may be particularly beneficial if restrictive metering rates are used and long vehicle queues are expected. However, this is not to be applied at the expense of inadequate acceleration length.

For loop ramps, it is recommended that the stop bar is positioned as close to the gore point as possible because of the importance of sight distance. This is provided that adequate acceleration distance is present.

[10] Part 2: Implementation Plan expands upon how to determine the required number of lanes.

[11] Section 2.1.4 details acceleration distance requirements.

Figure 2-1: Typical Ramp Meter Elements



2.1.3. Enforcement Area

An enforcement area is to be provided at every urban ramp where a ramp meter is installed (see Section 2.2 for tradeoffs). The enforcement area would typically be along the metered ramp; but in some cases, it could be provided nearby with line-of-sight to the ramp meter. The enforcement area typically is located on the right side and downstream from the stop bar. Figure 2-1 depicts the general position for an enforcement area, and Figure 2-2 details a typical enforcement area. It is suggested that the enforcement area begins 100 to 150 feet downstream of the stop bar, but the area's dimensions could be customized to fit site conditions.[12] While engineering judgment is to be applied when locating the enforcement area, the stop bar and red light running indicator on the back of signal assembly must be visible from the enforcement area.[13]

2.1.4. Acceleration Length

The minimum acceleration length must conform to the most recent edition of the AASHTO Green Book. The acceleration length is the distance between the stop bar and the ramp/freeway convergence point.[14] The acceleration length must be long enough to allow design vehicles to accelerate to within 5 miles per hour (mph) of the freeway's operating speed. Providing inadequate acceleration length is not allowed under any circumstance.

2.2. Design Criteria and Tradeoffs

Figure 2-3 through Figure 2-5 show typical metered ramp design. Each element with their full design criteria must be applied to all new ramps. For retrofit ramps, every effort is to be made on providing all elements with their full design criteria. However, this might not always be possible. For such cases, the following are the preferred tradeoffs.[15]

- If adequate acceleration length cannot be provided, a ramp meter is not to be installed. Storage length may be traded off (to a certain extent) for acceleration length.
- When there is inadequate ramp width, the required number of general-purpose lanes to meet practical capacity must first be provided. (Part 2: Implementation Plan defines capacity thresholds). An HOV bypass lane would be installed if there is adequate room remaining.
- If the ramp length is inadequate to provide the required minimum storage length, and the ramp width is inadequate to provide an additional lane for storage, then the HOV bypass lane could be traded off for storage length.
- The enforcement area can be traded off (to a reasonable law enforcement accommodation that is within the line-of-sight of the ramp meter) for providing the required number of general-purpose lanes and/or storage length.

[12] Any deviation from standard design considerations is to be discussed with and approved by NDOT.

[13] Design must also consider the enforcement area as a location for maintenance staff to safely park.

[14] For consistency of application, the convergence point is where the right edge of the ramp traveled way is 12 feet from the right edge of the rightmost through lane of the freeway mainline.

[15] All tradeoffs are to be discussed with and approved by NDOT prior to final design.

Figure 2-2: Enforcement Area Detail

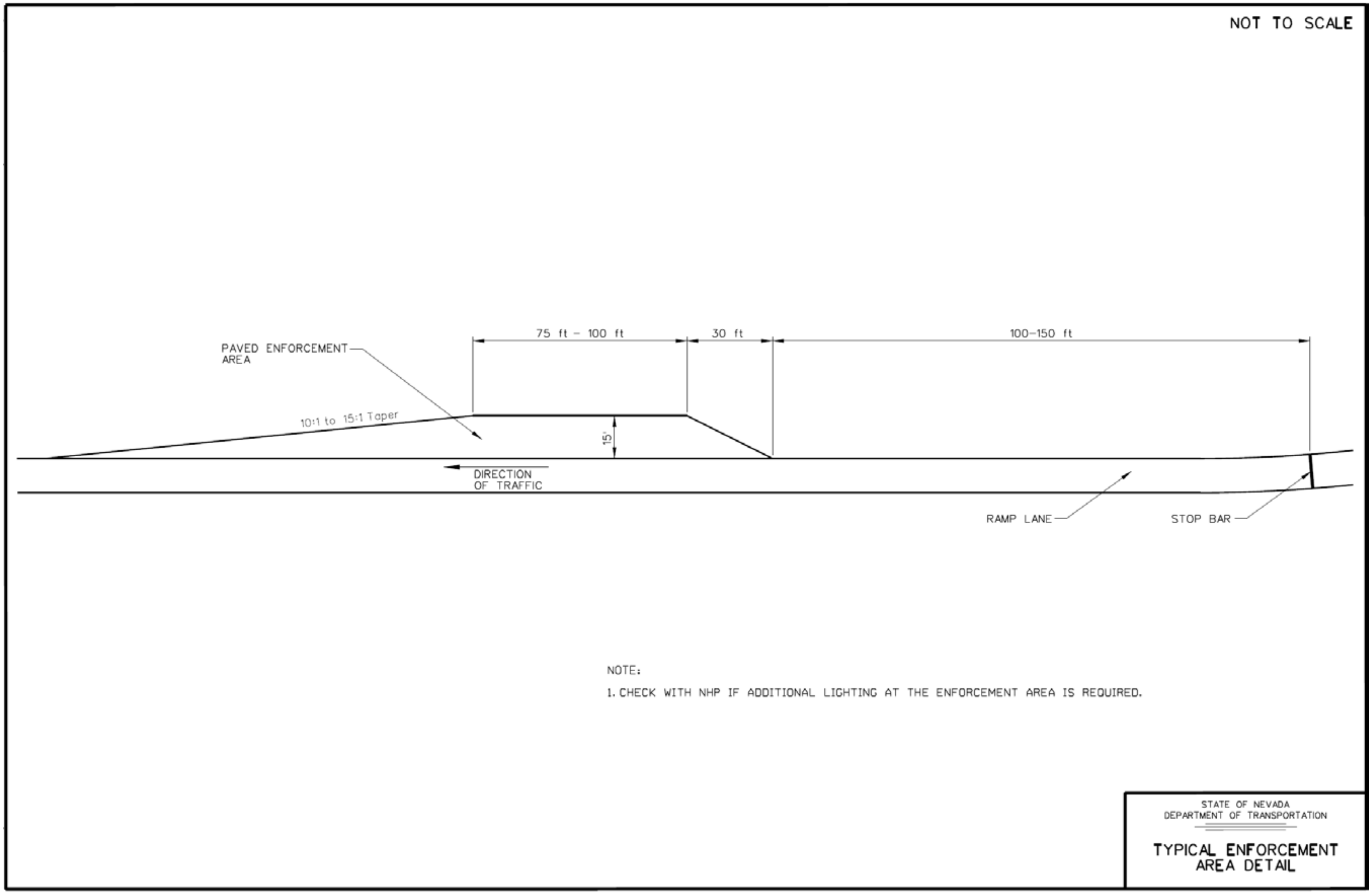


Figure 2-3: Typical One-Lane Metered Ramp Design

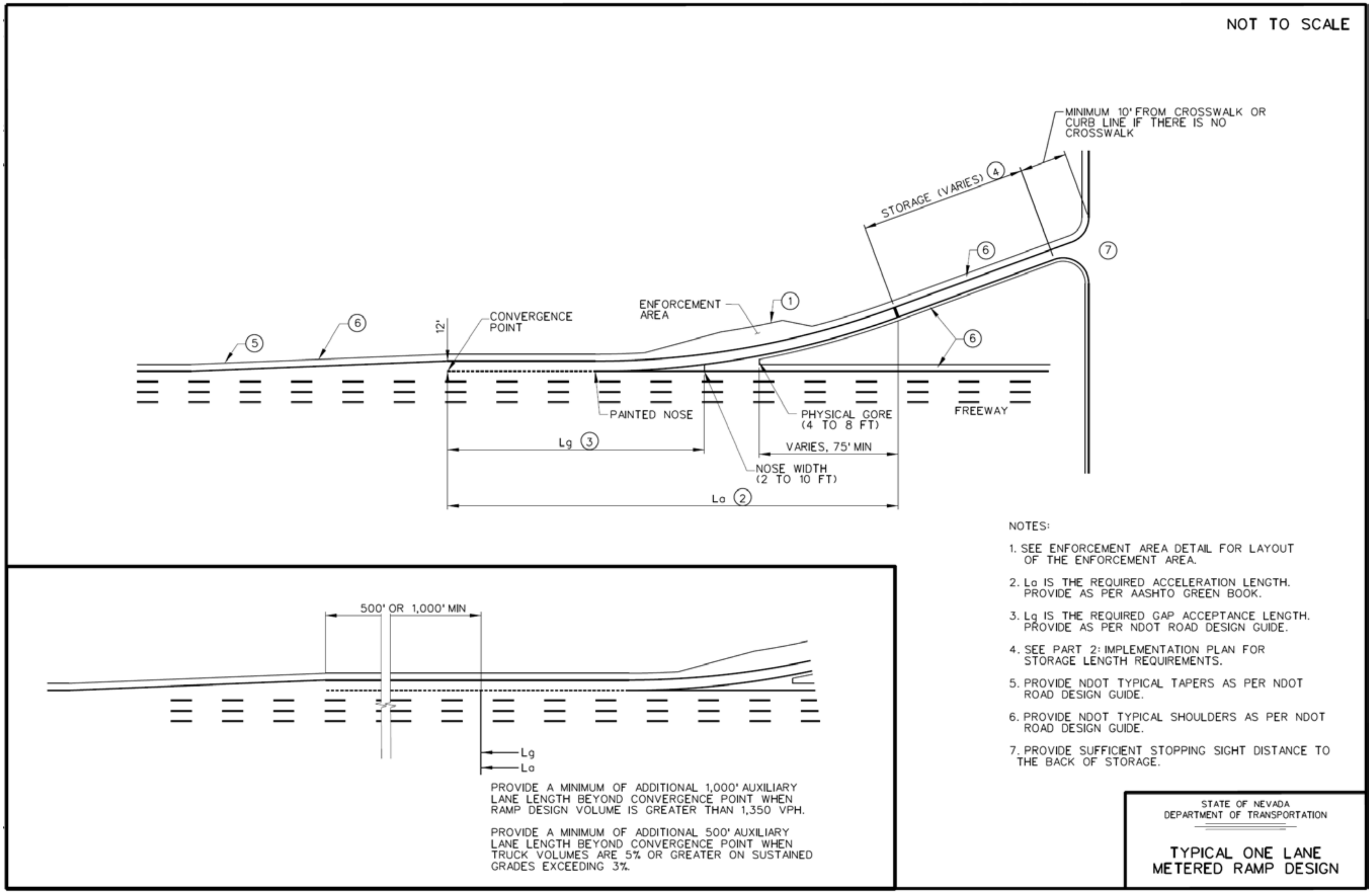


Figure 2-4: Typical Two-Lane Metered Ramp Design

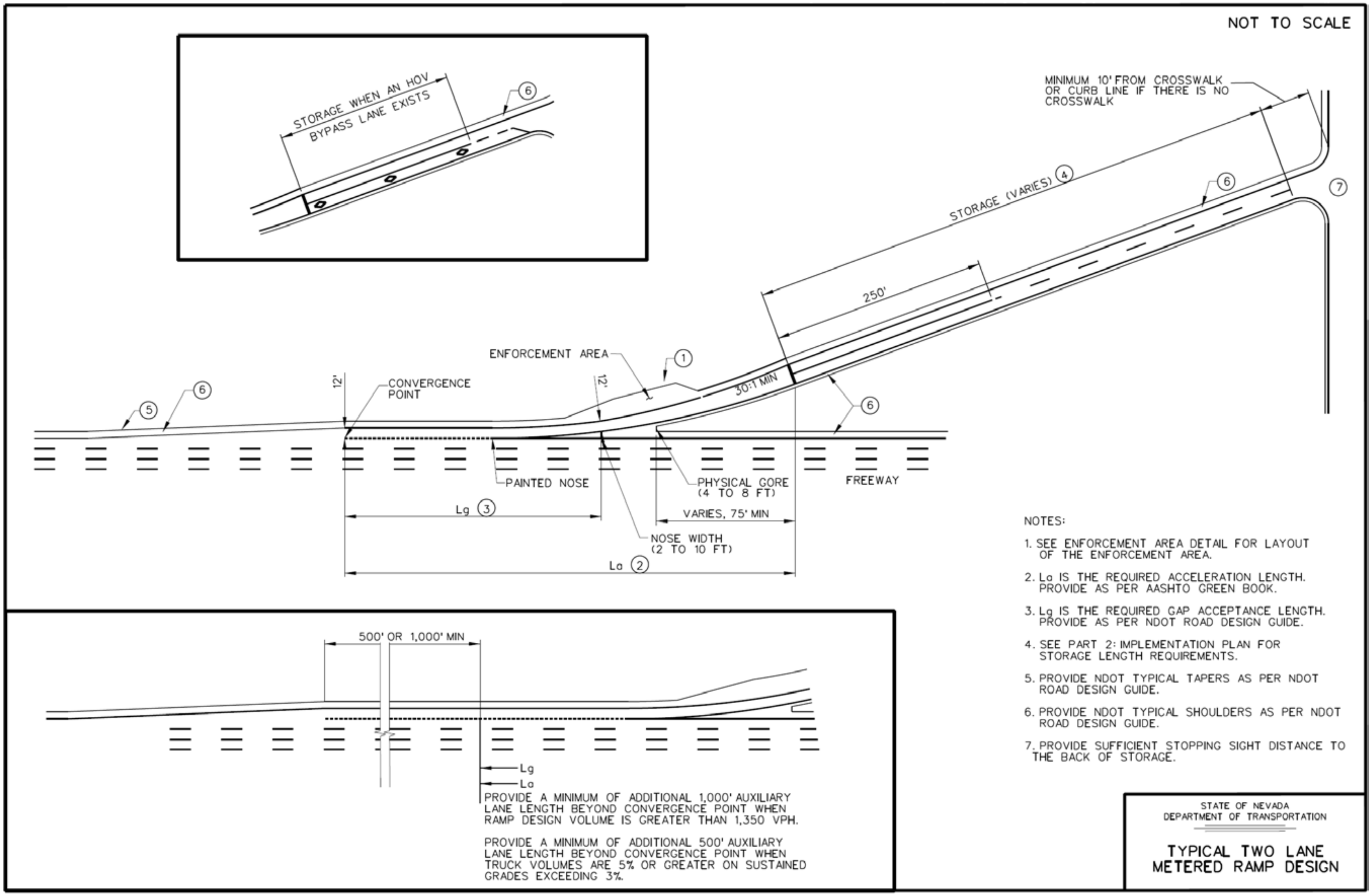
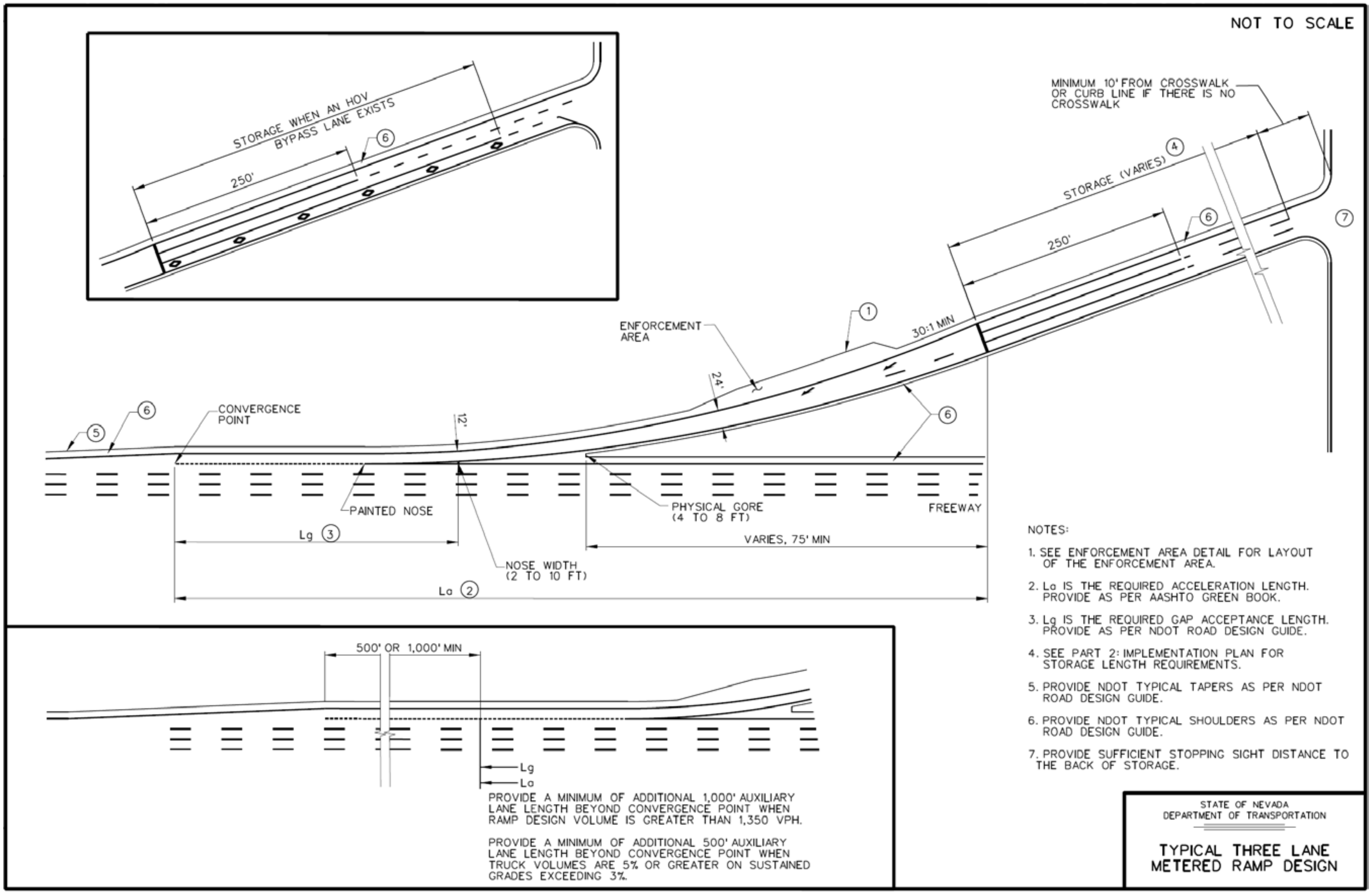


Figure 2-5: Typical Three-Lane Metered Ramp Design



2.3. Pavement Markings and Signs

The use of specific pavement markings and signs is dependent on the type of ramp (standard or freeway-to-freeway), number of lanes, presence of an HOV bypass lane, and number of turn lanes at the ramp/arterial intersection. Figure 2-6 through Figure 2-8 show pavement markings and signs for metered ramps. All metered ramps must be illuminated to make all pavement markings and signs on the ramp visible. NDOT-approved lighting is required.

2.3.1. Pavement Markings

Pavement markings on a metered ramp include the stop bar, lane line markings, and HOV markings. All pavement markings are to conform to the most recent editions of NDOT Standard Plans and the MUTCD.[16]

2.3.1.1. Stop Bar

A stop bar is required to designate the location for vehicles to stop. The stop bar must extend the entire width of all lanes, including the HOV bypass lane. Staggered stop bars are prohibited.

2.3.1.2. Lane Line Markings

Lane line markings are required to separate metered lanes. For metered ramps without an HOV bypass lane, a 250-foot-long solid lane line is required upstream of the stop bar. Beyond the 250 feet, lanes are separated by broken lane lines. HOV bypass lane is separated from general-purpose lanes with a solid lane line along the entire storage length.

2.3.1.3. HOV Markings

Pavement markings for an HOV bypass lane are required to clearly designate the preferential lane usage. The standard pavement marking for an HOV bypass lane is the diamond symbol.[17]

Pavement delineation at the entrance to the ramp is to lead the drivers into the general-purpose lanes (not into the HOV lane) to avoid single-occupant vehicles (SOVs) being trapped in the HOV bypass lane. For dual lefts that feed into a ramp with two general-purpose lanes and one HOV bypass lane, the design is to guide the dual lefts directly into the two general-purpose lanes (Figure 2-8). However, when dual lefts feed a ramp with one general-purpose lane and one HOV bypass lane, the most appropriate treatment is to be applied to ease access to the HOV bypass lane and reduce weaving on the ramp. If there are a considerable number of HOVs in the left turning traffic stream, the inner left turn lane could be designated for HOVs during times when the ramp meter is operating. In typical conditions, however, (i.e., where there is no HOV designation for the inner left lane) merging into the HOV bypass lane typically occurs on the metered ramp.[18] Simply not providing an HOV bypass lane (i.e., just providing two general-purpose lanes) is not an acceptable option.

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[16] NDOT Standard Plan T-38.1.7 provides pavement marking guidance specific to ramp metering, including HOV bypass lane details.

[17] NDOT Standard Plan T-38.1.7.

[18] Figure 2-8 provides the appropriate treatment for this situation. Additionally, when there are dual left turn lanes, the preferred option is to provide a three-lane ramp (even if the demands does not justify two general-purpose lanes), so that the dual lefts are directly guided into the general-purpose lanes.

Figure 2-6: Typical Pavement Markings and Signs: No HOV Lane

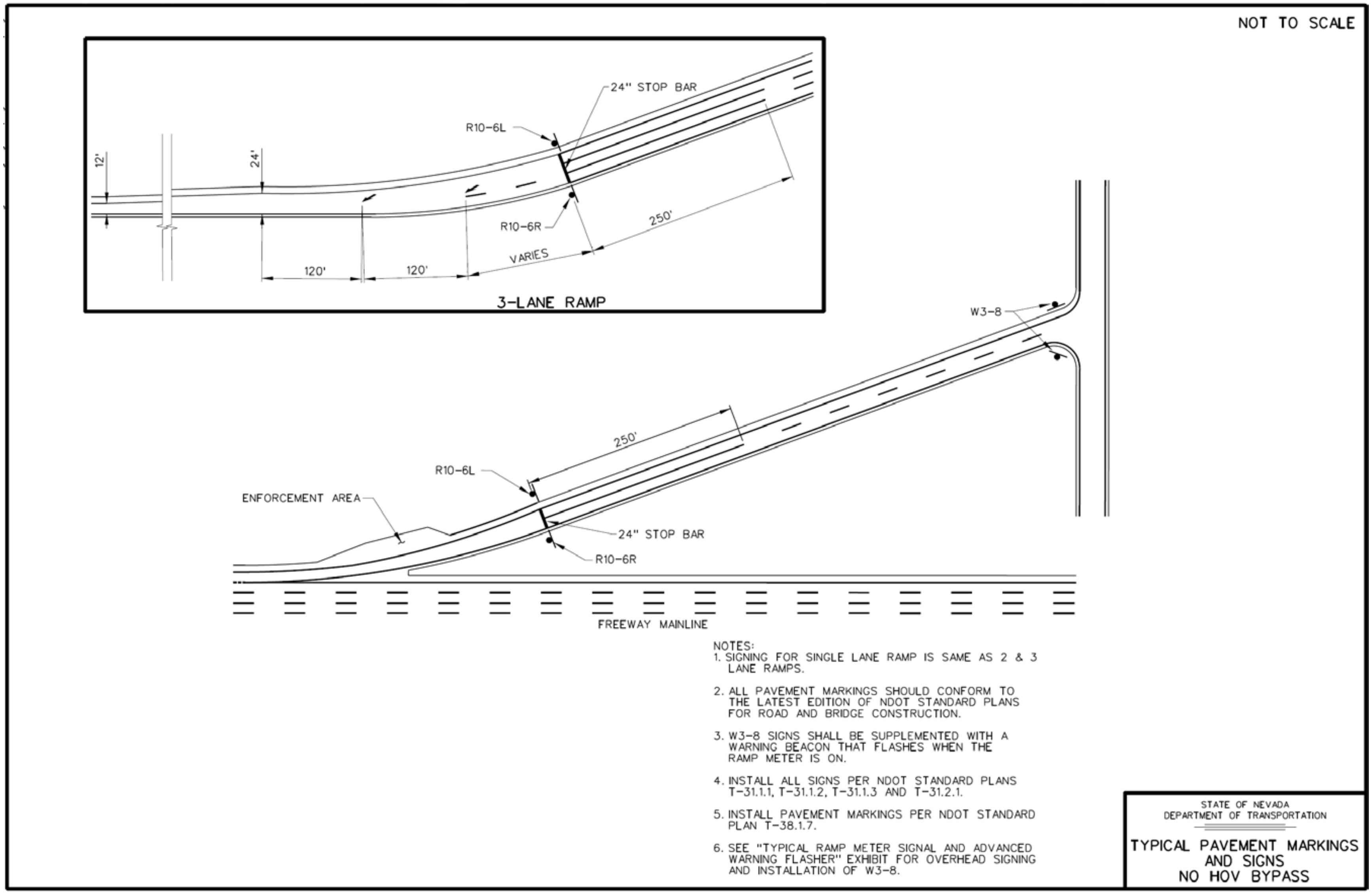


Figure 2-7: Typical Pavement Markings and Signs: Single Left Lane

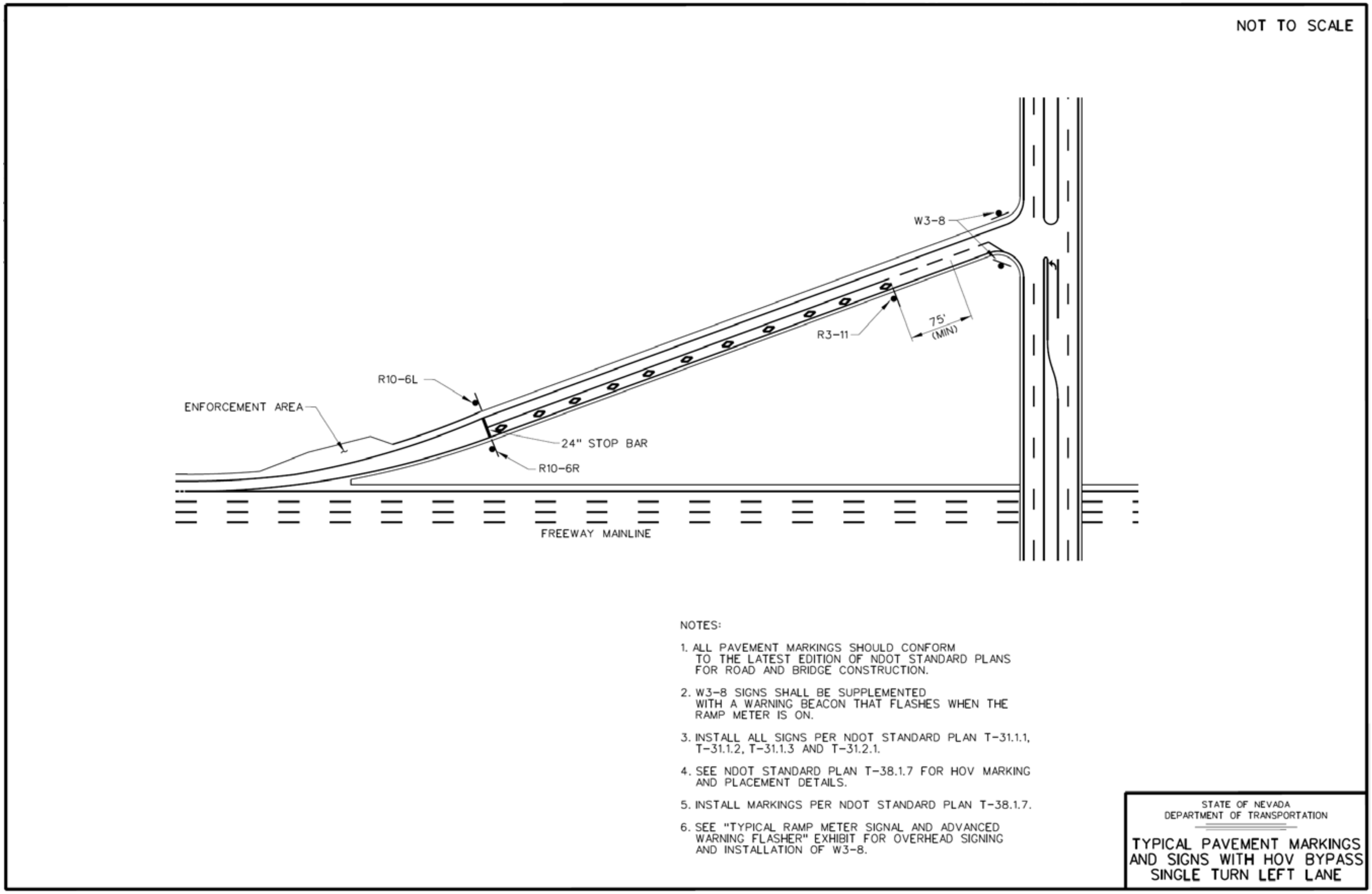
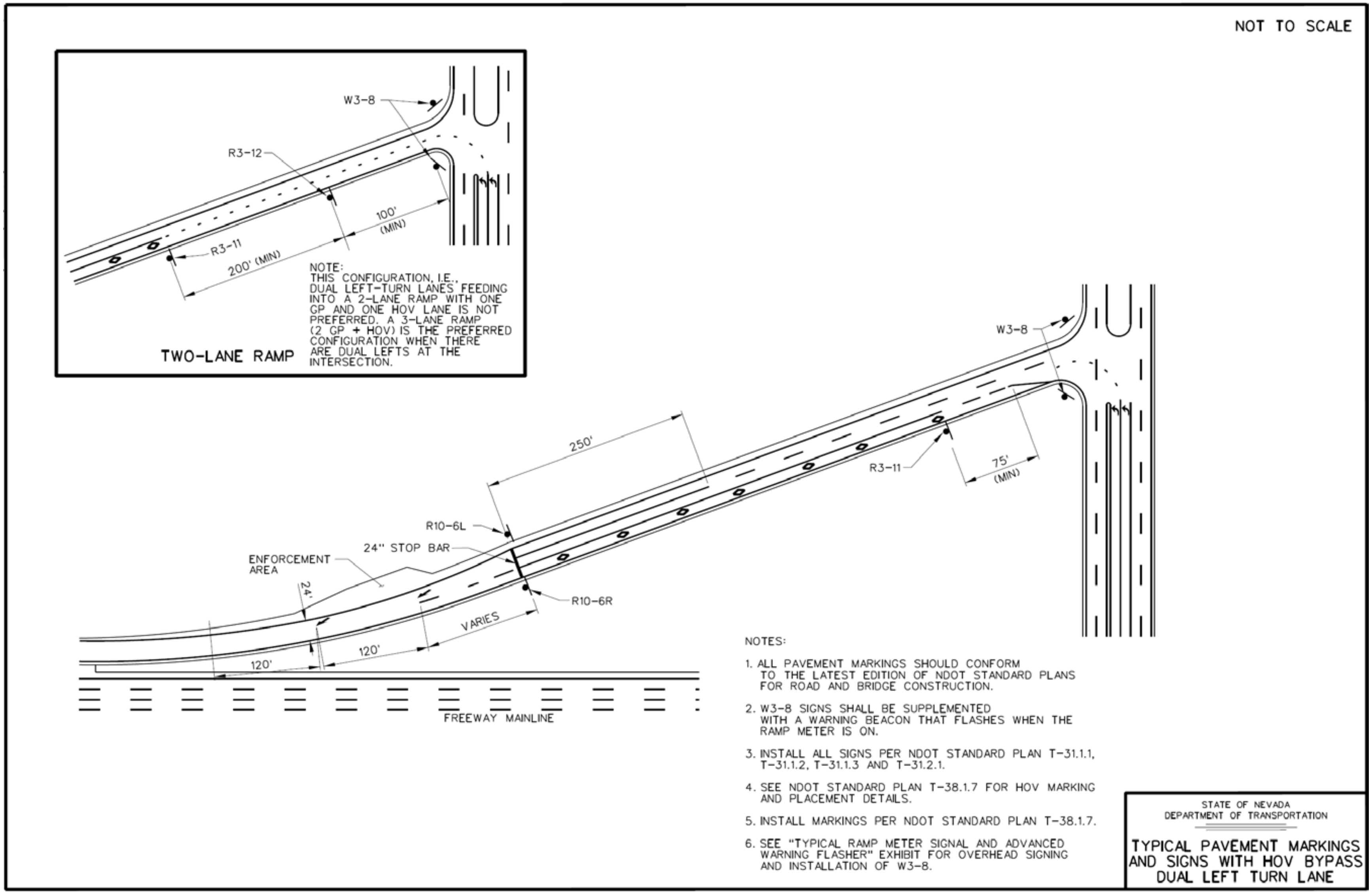


Figure 2-8: Typical Pavement Markings and Signs: Dual Left Lane



2.3.2. Signs

There are a variety of signs used for ramp metering. The types of signs depend on the type of ramp meter design. All ramp meter signs are to be in accordance with the most recent edition of the MUTCD and Nevada Sign Supplement. Sign installation must conform to the most recent edition of the NDOT Standard Plans.

2.3.2.1. Regulatory Signs for Ramp Metering

Figure 2-9 depicts the regulatory ramp metering signs with their identification codes.

Figure 2-9: Regulatory Ramp Metering Signs

R10-6R

R10-6L

R10-29

RNV33-8

R3-11[19]

R3-12

A "STOP HERE ON RED" sign is to be placed on both sides of the entrance ramp at the stop bar. Because "one vehicle per green" is the typical release rate, a "1 VEHICLE PER GREEN EACH LANE" sign is to be placed on the signal mast arm for each general-purpose lane. For the HOV bypass lane, a "HOV 2+ ONLY 1 VEHICLE PER GREEN" sign is to be placed on the

[19] Other HOV signs in the MUTCD R3-11 family are allowed if and when appropriate, and as approved by NDOT.

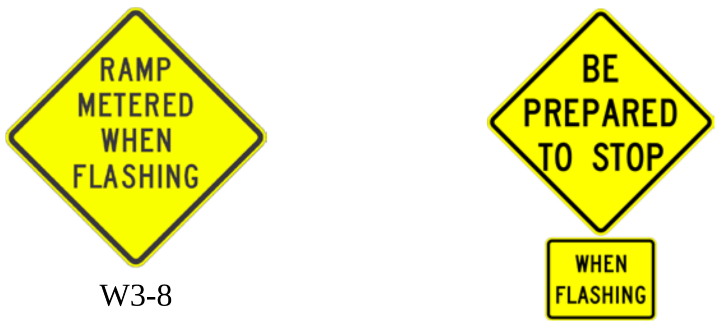
signal mast arm above the HOV bypass lane. Figure 2-16 provides installation details of these signs.

HOV signs for ramp meters are to clearly indicate the HOV bypass lane so motorists can make appropriate lane choices before lane restrictions occur. An "HOV 2+ ONLY WHEN METERED" sign is to be placed at the entrance of the HOV bypass lane to indicate HOV restriction when metering is on. When dual left turn lanes feed a ramp with one general-purpose lane and one HOV bypass lane, an "HOV 2+ LANE AHEAD" sign is to be used (Figure 2-8). A "MOTORCYCLES ALLOWED" plaque (R3-11P) is to be attached to the HOV signs.

2.3.2.2. Advance Warning Signs for Ramp Metering

Advance warning signs provide motorists advanced notice that ramps are metered (Figure 2-10). Advanced warning signs are to be deployed with a 12-inch yellow flashing beacon that is activated during metered periods to alert motorists of the upcoming controlled ramp.

Figure 2-10: Advanced Warning Ramp Metering Signs



W3-8

W3-4 and W16-13P Plaque

For typical ramp metering (i.e., arterial-to-freeway), a "RAMP METERED WHEN FLASHING" sign is to be posted on both sides of a ramp entrance and is to be visible from the adjacent arterial. Figure 2-16 shows installation detail for this sign.

For freeway-to-freeway ramp metering, it is critical that sufficient advance warning for stopping distance and storage is provided for motorists.[20] A recommended practice is to install a sequence of two signs on the freeway-to-freeway connector. A "RAMP METERED WHEN FLASHING" sign is typically installed downstream (recommended at 100 feet) from the point of the exit gore area. A"BE PREPARED TO STOP WHEN FLASHING" sign is suggested to be installed downstream of the "RAMP METERED WHEN FLASHING" sign, and the recommended placement would be at least 400 to 600 feet downstream of the "RAMP METERED WHEN FLASHING" sign and at least 1,000 feet upstream of the stop bar.

2.4. Equipment

Ramp meter equipment consists of detection devices, a ramp controller assembly, a signal assembly, and an advanced flasher. Cables and pull boxes are required to connect all equipment to the controller. A closed circuit television camera (CCTV) is required to monitor the ramp

[20] Freeway-to-freeway ramp metering is currently not being implemented in Nevada, but it may be considered in the future.

meter operation. At a minimum, CCTV needs to be able to view all ramp lanes, ramp queues, and adjacent ramp terminal intersection. Figure 2-11 through Figure 2-13 detail typical equipment layout for one-, two-, and three-lane metered ramps.

2.4.1. Detection

Vehicle detection is required at specific locations on the metered ramp and mainline. Detection is to be implemented in the form of induction loops. Video detectors, radar detectors, or other detection devices can be implemented with the approval of NDOT. The detectors are shown as "detection zones" in Figure 2-11 through Figure 2-13.[21]

2.4.1.1. Demand Detectors

Demand detectors (also referred to as input detectors) are located in each metered ramp lane in the stop bar area. The trailing edge of the demand detection zone must be 3 feet downstream of the center of the stop bar. Demand detectors operate as typical traffic signal stop-bar detectors. Demand detectors sense the vehicle's presence at the stop bar and initiate a green signal for that specific lane.

2.4.1.2. Passage Detectors

Passage detectors (also referred to as output detectors) are installed immediately downstream of the stop bar. The leading edge of the passage detection zone must be 15 feet from the center of the stop bar (i.e., 12 feet from the trailing edge of the demand detectors). The passage detection zone provides coverage downstream of the stop bar in each metered lane. The purpose of passage detectors is to terminate the green interval after a vehicle clears the stop bar. These detectors also count the number of vehicles that enter the freeway.

2.4.1.3. Advanced Queue Detectors (AQDs)

Advanced queue detectors (AQDs) monitor excessive queues that cannot be contained within the queue storage area. These detectors provide input to maximize the metering discharge rate or temporarily turn-off metering ("flush") to clear excessive queues. This detection process limits queues from spilling onto the local streets and disrupting arterial operations. An AQD zone is to be located at 100 to 300 feet from the arterial's curb line. When an HOV bypass lane exists, the AQD is typically located at the beginning of the HOV bypass lane. Intermediate queue detectors could be added to the ramp to identify when the queues are beginning to fill the ramp capacity.

2.4.1.4. Mainline Detectors

Mainline detectors provide freeway occupancy, speed, and volume information that are used to select the traffic-responsive metering rate. These detectors also provide data for system-wide ramp metering and incident detection algorithms. While placement of mainline detection varies, it is typically 500 feet upstream of the entrance ramp gore area.

2.4.1.5. Exit Ramp Detector

Exit ramp detectors are used for system-wide traffic responsive ramp metering algorithms. Exit ramp detectors also provide traffic count data for the Freeway Management System (FMS).

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[21] The placement of detectors must be reviewed and approved by the NDOT Operations Division.

2.4.1.6. *Entrance Ramp Detection for Ramps without Meters*

For system-wide traffic responsive ramp meters, detection is required on entrance ramps that are not metered. Accurate corridor count data ensures that the proper metering rates are implemented at the metered ramps.

2.4.2. Ramp Controller Assembly

The ramp controller assembly consists of a cabinet, controller, load switches, input files, loop amplifiers, and other devices similar to a traffic signal at an intersection. The ramp controller acts as both a data station and a signal controller. NDOT uses type 170s for ramp controllers.

Illustrated in Figure 2-14 and Figure 2-15, the controller cabinet must be placed where it is easy to access for maintenance, allows a technician to see the signal heads, does not block a vehicle's sight distance, and is protected from errant vehicles. The typical location is on the right side of the ramp. Cabinets that are not protected by a guardrail are to be located outside of the clear zone.

Other factors that influence the location of the ramp controller assembly include grade, drainage considerations, accessibility to a power source, and communication with the traffic management center. Communication can be provided via telephone lines, fiber-optics, microwave, or radio frequencies.

2.4.3. Signal Assembly

A mast arm style signal pole with overhead signal heads must be used on all metered ramps, including one-lane ramps. One signal head is located over each metered lane. This includes HOV bypass lane because they are metered. All signal poles are typically located in the clear zone to reduce the potential for "knock-down" or protected by guard or barrier rail. As shown in Figure 2-11 through Figure 2-13, the distance from the stop bar to the signal faces is typically 60 feet.[22]

A minimum of two signal faces is required (i.e., red and green) regardless of the number of lanes. Because metering operations are enforced, a single red light is used on the opposite side of the signal pole for each lane.[23] Figure 2-16 details the typical ramp meter signal and advanced warning flasher assembly.

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[22] The allowable range of distance and the maximum height of the signal housing over the roadway are to be consistent with the most recent edition of the MUTCD.

[23] This allows the enforcement officer located downstream of the ramp meter to know when the red signal indication is active for each lane.

Figure 2-11: Typical Equipment Layout: One-Lane Metered Ramp

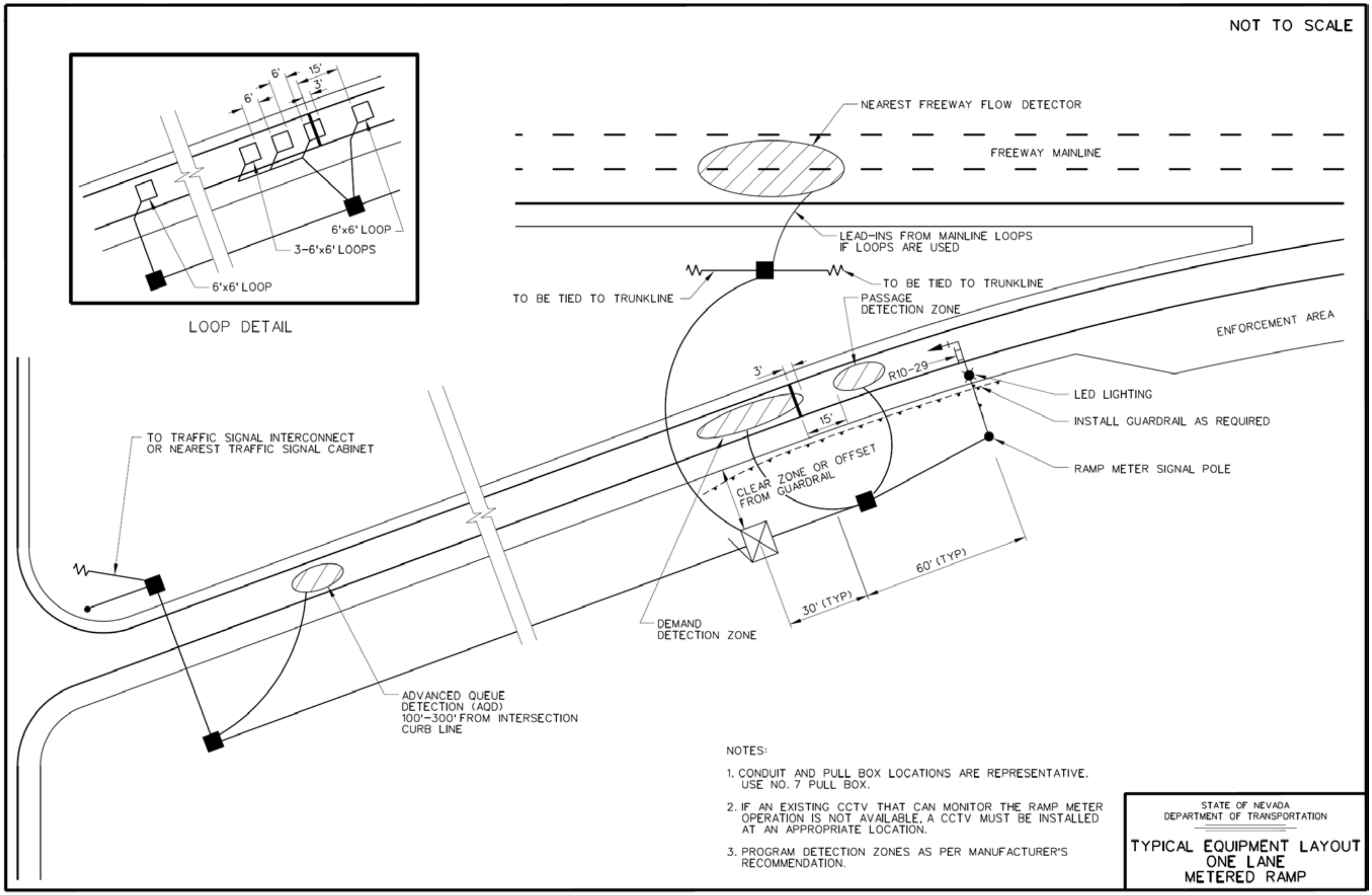


Figure 2-12: Typical Equipment Layout: Two-Lane Metered Ramp

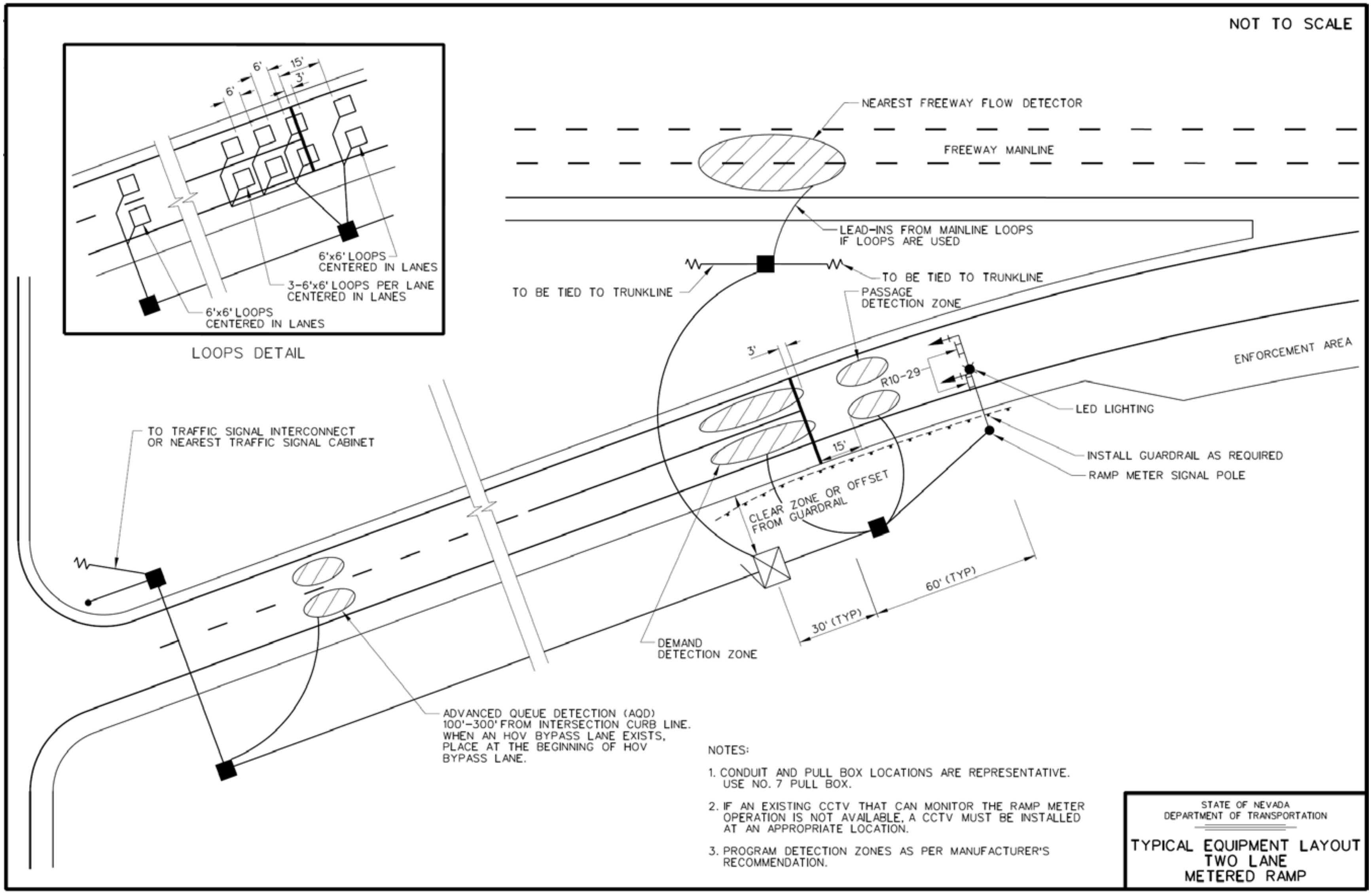


Figure 2-13: Typical Equipment Layout: Three-Lane Metered Ramp

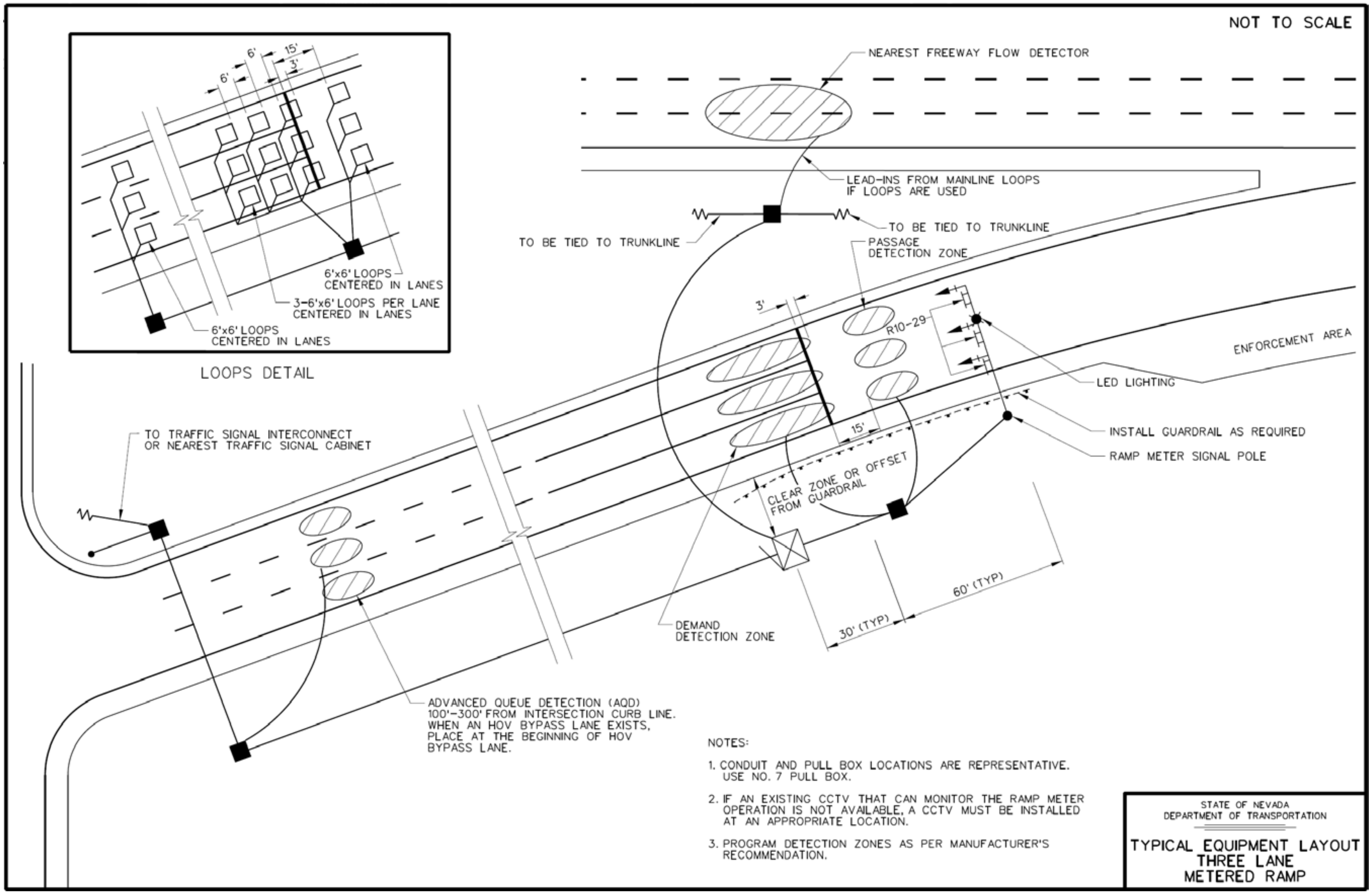


Figure 2-14: Typical Controller Cabinet Configuration

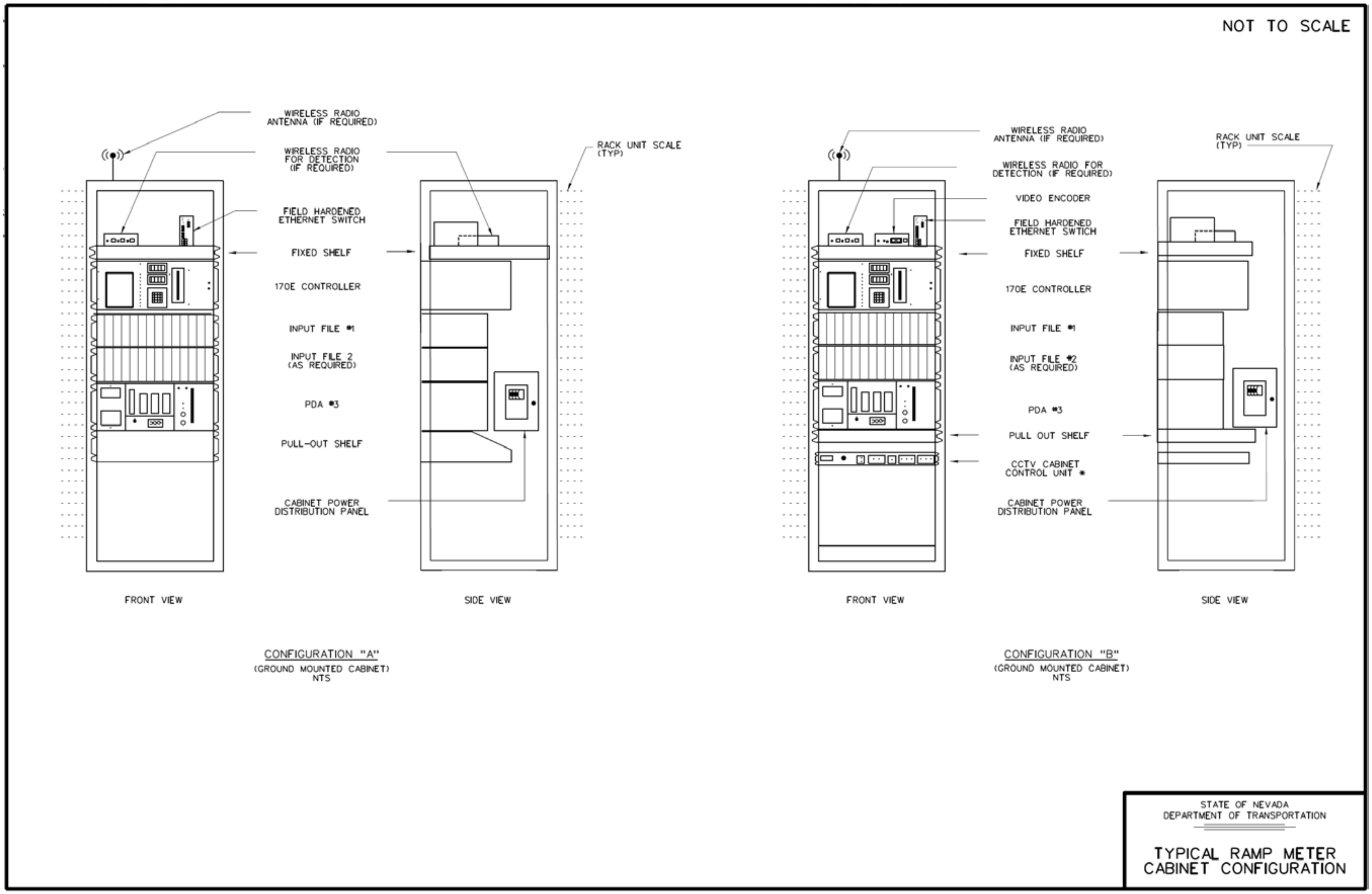


Figure 2-15: Typical Controller Cabinet Detail: Foundation

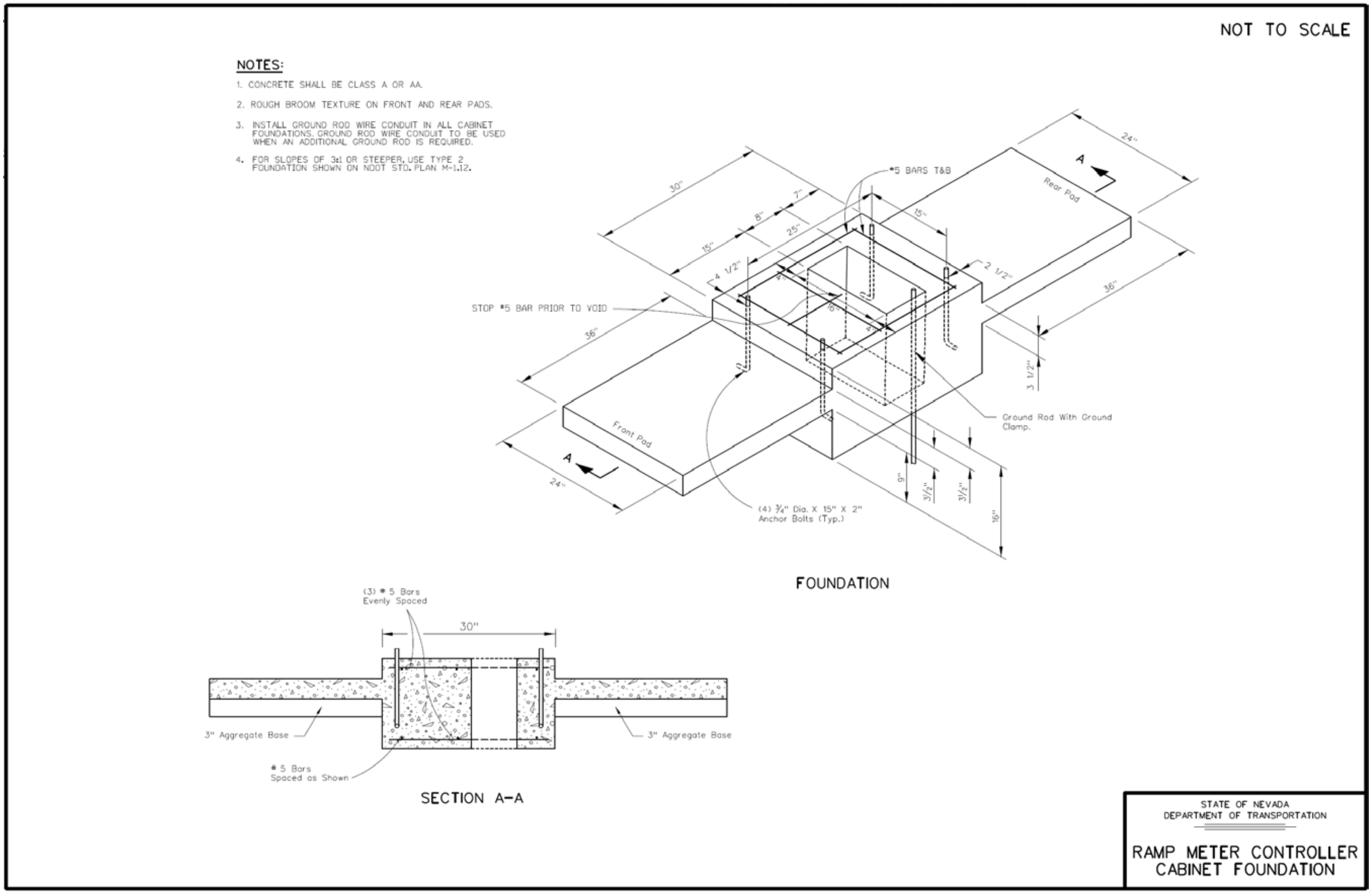
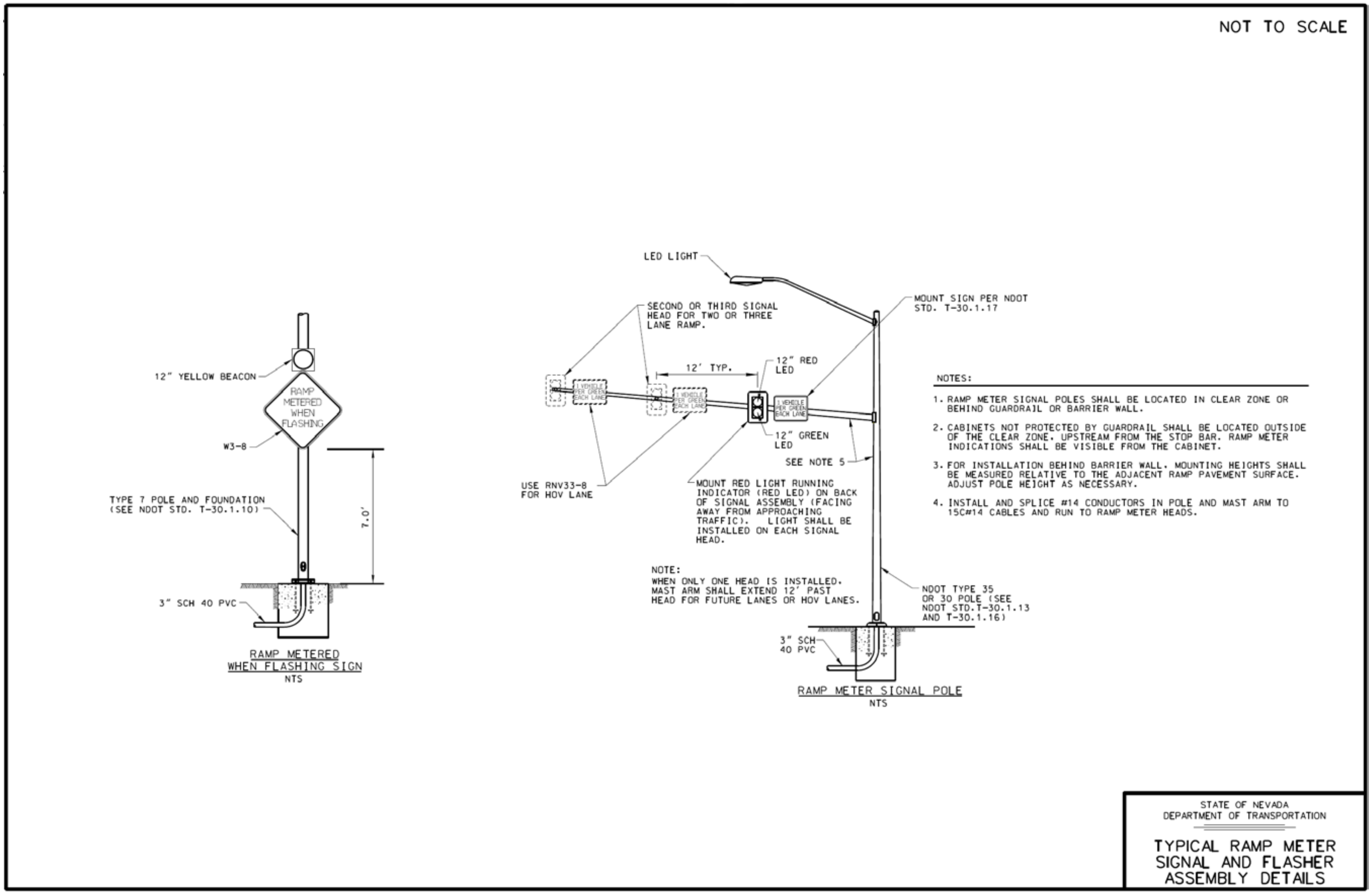


Figure 2-16: Typical Ramp Meter Signal and Advanced Warning Flasher Details



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