NCHRP 03-123 Technical Memorandum for Task 2

Summary of Effective Practices

to the

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM (NCHRP)

On Project

NCHRP 03-123

Proposed Practices for the Application of Dynamic Lane Use Control

The information contained in this report was prepared as part of NCHRP Project 03-123, Proposed Practices for the Application of Dynamic Lane Use Control, National Cooperative Highway Research Program.

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January 31, 2017

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Acknowledgements

This technical memorandum was prepared by a team from the Texas A&M Transportation Institute led by Dr. Sue Chrysler in collaboration with Mr. Chuck Fuhs as part of National Cooperative Highway Research Program (NCHRP) Project 03-123, *Proposed Practices for the Application of Dynamic Lane Use Control*. The NCHRP is supported by annual voluntary contributions from the state Departments of Transportation. The work was guided by a project oversight panel and managed by Mr. Ray Derr, NCHRP Senior Program Officer.

Disclaimer

Introduction

NCHRP Project 03-123 *Proposed Practices for the Application of Dynamic Lane Use Control* will develop recommendations for the application of dynamic lane use control based upon their human factors implications. The project will be complete in June 2018. This document presents the findings of an early task in the project to document the state of the practice of dynamic lane use control for freeway active traffic management applications. This *Summary of Effective Practices* presents information on how dynamic lane use control is addressed in the Manual on Uniform Traffic Control Devices (MUTCD) (*1*) and how six United States (U.S.) agencies have applied dynamic lane use on their facilities.

The focus of this current project (NCHRP project 03-123) is active traffic management (ATM) or active travel demand and management (ATDM) operations. NCHRP Project 03-114 *Planning and Evaluating Active Traffic Management Strategies* identified a wide array of operational strategies as shown in Figure 1 (*2*). A 2014 FHWA document on ATDM provides definitions for the strategies used by the research team to categorize dynamic lane use control (DLUC) operations as shown in Table 1 (*3*, *4*).

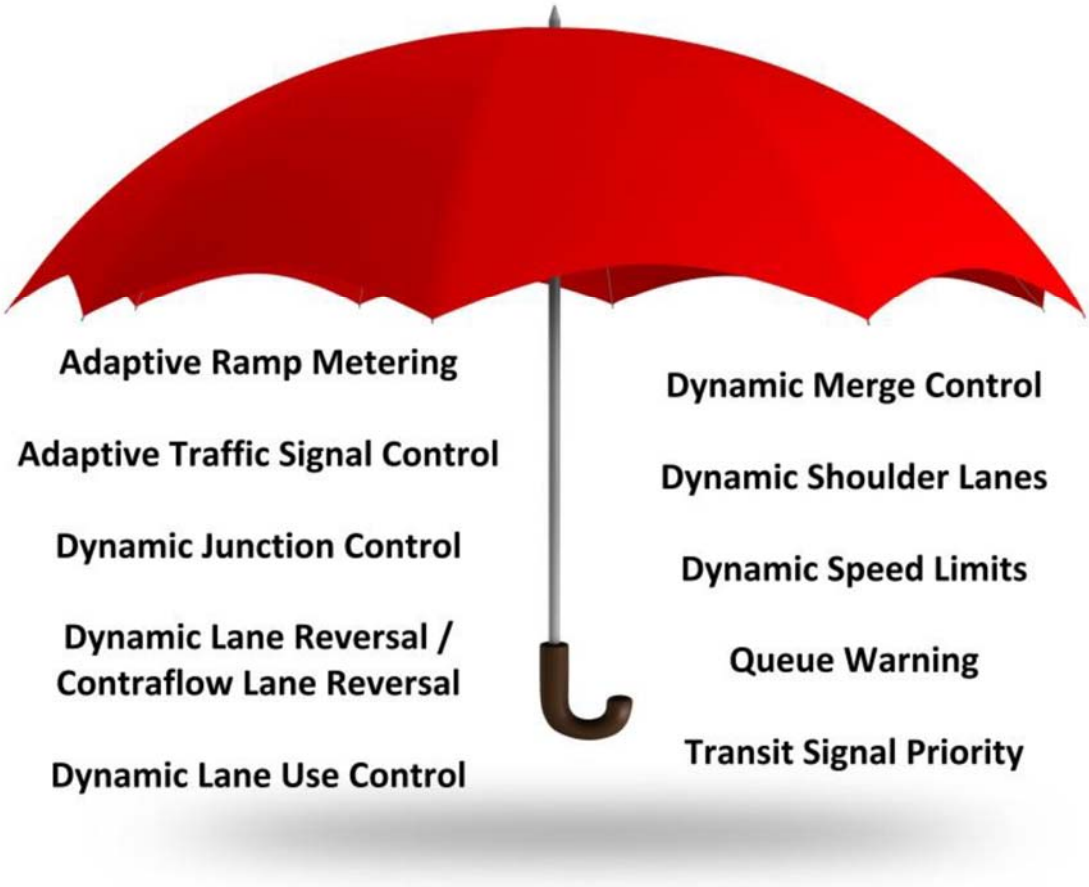


Figure 1. ATM operational strategies identified in NCHRP 03-114 (Figure from 03-114 report).

Table 1. ATM Strategies as defined by FHWA (adapted from 4).

Strategy	Definition
Dynamic lane use/shoulder control	The dynamic opening of a shoulder lane to traffic or dynamic closure of travel lanes on a temporary basis in response to increasing congestion or incidents.
Dynamic speed limits	The dynamic change in speed limits based on road, traffic, and weather conditions.
Queue warning	The dynamic display of warning signs to alert drivers that congestion and queues are ahead.
Adaptive ramp metering	The dynamic adjustment of traffic signals at ramp entrances to proactively manage vehicle flow from local-access roads
Dynamic junction control	The provision of lane access based on highway traffic present and merging/diverging traffic to give priority to the facility higher volume to minimize the impact of the merging/diverging movement.

Applications of Dynamic Lane-Use Control for Freeway ATM

The research team only included strategies that utilize dynamic lane-use controls in their operations. This current summary is focused on freeway ATM applications as directed by the panel.

For the purpose of the current project, the research team used the following categories of ATM operations. These groups were selected to reflect the fact that the longitudinal spacing, lateral position, and sign message displays will differ for each of these categories.

- Temporary lane closures for incident management or junction control.
- Dynamic speed limits to promote speed harmonization, warning of slow speeds or queues ahead.
- Reversible lanes for freeway preferential lanes or arterial use.
- Part-time shoulder use, also called hard shoulder running.

The research team consulted the TRB Committee on Managed Lanes and the joint sub-committee on Active Traffic Management to obtain the most current listing of ATM operations in the U.S. Two FHWA reports in process were also consulted to identify U.S. and international operations (*2*, *5*).

Manual on Uniform Traffic Control Devices

Existing MUTCD Content

The 2009 MUTCD contains information on lane-use control signals and related changeable message signs in these general areas:

- Chapter 4M Lane-Use Control Signals in Part IV Highway Traffic Signals.
- Chapter 2L Changeable Message Signs in Part II Signs.

- Chapter 4K. Highway Traffic signals at Toll Plazas, Section 4K.02 Part IV Highway Traffic Signals.
- Section 2B.26 Reversible Lane Control Signs in Part II Signs.
- Section 2G. Preferential Lane Regulatory Signs in Part II Signs.
- Section 6F.61 Arrow Boards in Part VI Temporary Traffic Control.

Lane-use control is addressed most directly in section 4M where the basic meanings of the signal indications are provided as shown in Table 2.

Table 2. MUTCD meanings of lane-use control signal indications (Section 4M.02).

Steady DOWNWARD GREEN ARROW	A road user is permitted to drive in the lane over which the arrow signal indication is located.
Steady YELLOW X	A road user is to prepare to vacate the lane over which the signal indication is located because a lane control change is being made to a steady RED X signal indication.
Steady RED X	A road user is not permitted to use the lane over which the signal indication is located and that this signal indication shall modify accordingly the meaning of other traffic controls present.

The Appendix to this document contains details on the material included in each of the MUTCD sections listed above. The following section provides discussion on questions being explored regarding DLUC.

Lane Use Control Traffic Control Device Types

Lane use control is fundamental to maintain good traffic flow and safety. Static lane-use control signs and markings were some of the earliest traffic control devices used. The first dynamic lane-use control applications utilized traditional traffic signal heads. As such, the MUTCD Part on signals contains the most detailed material about the operation of DLUC signals. With the advent of higher resolution changeable message signs, more and more agencies are using dynamic lane-use control signs rather than signals. Because dynamic lane-use controls are used as part of incident management plans, the Illinois Tollway is considering a request to experiment under Part VI of the MUTCD Temporary Traffic Control. As states and FHWA continue to grapple with where these devices fit in the MUTCD, operators have had to apply existing language to new operations. Most ATM facilities operating today with dynamic lane-use signs have filed a request for experimentation with FHWA, especially for use of novel yellow transition phase indications.

The MUTCD addresses lane control as both a regulatory and a guide sign function. The MUTCD addresses lane control in general by presenting information about Intersection Lane Control regulatory signs (Section 2B.19, see Figure 2) and arrow-per-lane and destination guide signs (Section 2E.21 see Figure 3 for illustration of an arrow per lane guide sign). Lane control is also included in Part 4 Signals as it applies to through and turning movement indications on signal faces (Figure 4). Lane control is also addressed in Part 6 Temporary Traffic Control with regards to lane closures (see example in Figure 5).

Identifying and resolving what type of traffic control device dynamic lane-use controls are would assist in refining the requirements for the device. Is it a signal, a sign, or a temporary traffic control device? From that categorization, practitioners and standards committees can apply the MUTCD principles of design and operation appropriate for that type of device. Critical design decisions concerning default state and arrow direction will follow from the classification of DLUC into a specific category of traffic control device.

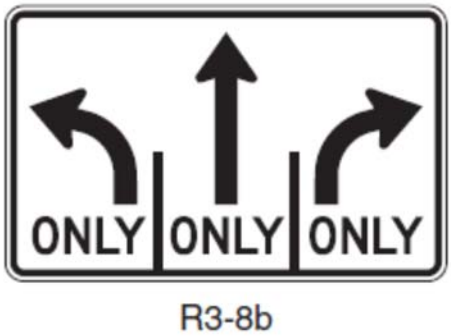


Figure 2. Example intersection lane control regulatory sign from MUTCD.

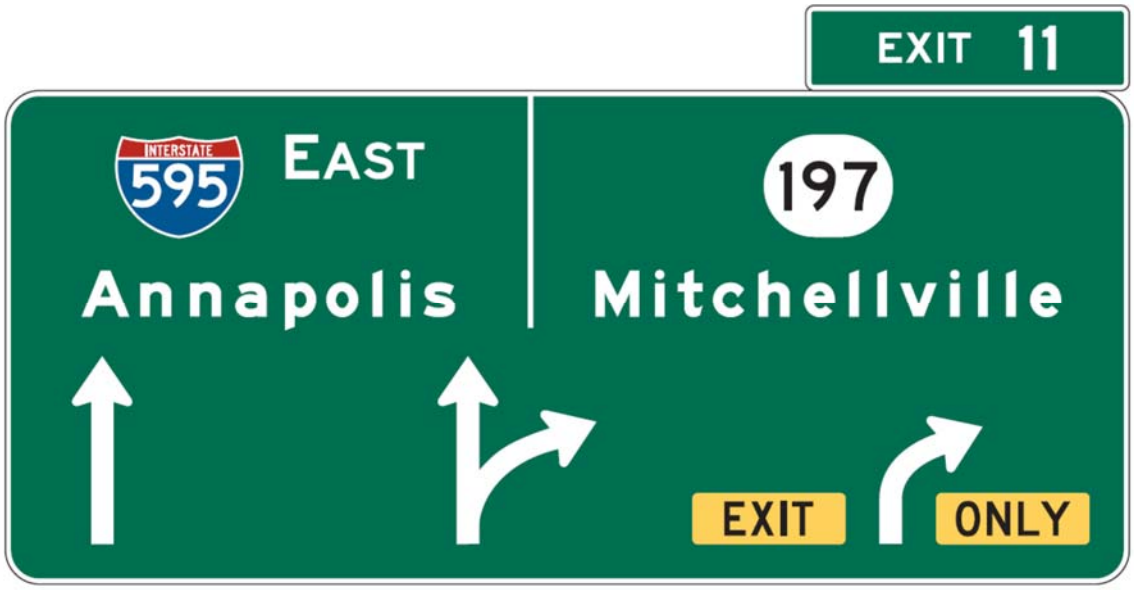


Figure 3. MUTCD figure illustrating arrow-per-lane guide sign (MUTCD Figure 2E-3).

Figure 4. Traffic signal indication for continuous movement (MUTCD Section 4D.09, Figure 4D-2 Section C).

Figure 5. Arrow Panel and CMS Arrow Board to indicate lane closure for work zones (MTUCD Part VI Temporary Traffic Control).

Dynamic Lane Use Control Hardware

Section 4M.03 of the MUTCD specifies that lane-use control signal faces shall be 18 inches for typical applications greater than 40 mph, shall have an opaque background, and shall be clearly visible for 2,300 feet at all times under normal atmospheric conditions, unless otherwise physically obstructed. If the length of lane controlled by the signal is greater than 2,300 feet, then additional signals must be placed such that at least one signal, and preferably two, will be visible at all times. Sizes larger than 18 inches are allowed to facilitate symbol recognition appropriate to signal spacing.

Four general types of lane-use controls were observed by the research team in reviewing freeway ATM, arterial, bridge, and tunnel applications. With the exception of some arterial reversible lanes, all of the ATM operations reviewed used changeable message signs (CMS), rather than traditional signal heads, to control the lane use. The following are the four types of lane controls identified:

- **Large lane control panels.** Overhead mounted dynamic message panels that are composed of a variable matrix display that can create both arrow and X symbols as well as words (see example in Figure 6). They are commonly used along mainline sections of freeways with a 55 mph or greater posted speed. They are at least 3 feet square, with the most typical size being 4 feet square.
- **Small lane control panels.** Smaller panels composed of various designs to operate only for the display of an arrow or X (see example in Figure 7). They are found on both controlled access roadways and arterial streets. They do not appear to be sized for any specific design speed, but are more commonly found on lower speed (40-55 mph) tunnels and bridges.
- **Standard traffic signal.** A two-or three-lenses signal head is mounted over each lane, usually in a horizontal orientation (see examples in Figure 8 and Figure 9). Applications are typically on bridges and tunnels. The signals may also be found in a few instances along both side walls of tunnels where there are only two directional lanes. These lane-use controls were only found in bridge and tunnel applications.
- **Runway light.** Due to the limited clearance in tunnels, a long-practiced strategy has included the use of small beacons or lights located over each lane mounted almost flush with the tunnel ceiling (see example in Figure 10). Spacing is generally consistent with other tunnel and bridge applications. Runway lights are not employed outside these restricted height settings.

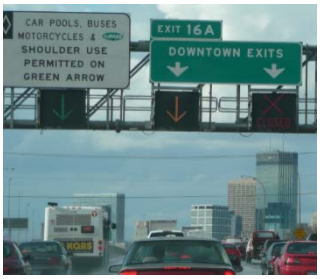


Figure 6. I-35W in Minneapolis.

Figure 7. Boston I 90, not matrix CMS allowing only X or arrow.

Figure 8. Example of three-lens traffic signal used on a bridge in Norfolk, VA.

Figure 9. Example of a two-lens traffic signal used on I-395, 3rd Street Tunnel in Washington DC.

Figure 10. Examples of runway lights in Lincoln Tunnel, Rte 495 New Jersey.

ATM Applications

Europe

Europe has significant long-term experience in ATM applications. Specifically, DLUC applications have been part of the vocabulary of overall traffic management for controlled access roadways in urban and intercity routes. Countries with the longest experiences includes the Netherlands, Germany, England, and Denmark. Mainline ATM applications to facilitate speed harmonization are most widespread in the Netherlands with many of the country's motorways equipped with installations similar to the example shown in Figure 11. Long-standing experiences have resulted in regional and national consistencies of practice. Some aspects appear to be consistent within the EU, such as pictograms applied within overhead lane controls and side mounted dynamic message signs (DMS) panels as shown in Figure 11. This review also shows that most DLUC devices are blank when not in use.

Figure 11. Example ATM applications in the Netherlands (2).

Overhead lane controls are also found in application on many tunnels and bridges in such countries as Germany, Italy, Austria, Czech Republic, Slovenia, France, England, Norway, Sweden, Denmark, and Switzerland. Overhead gantries have also been employed in conjunction with DLUC installations as a traffic control strategy through major construction projects such as the ring road in Copenhagen a decade ago (*2*).

Shoulder-mounted changeable message signs are being used for hard shoulder running applications in the United Kingdom and Germany as shown in Figure 12 (6) and Figure 13 (7). Figure 12 demonstrates that the CMS can be used to communicate lane closure or another message such as downstream road work.

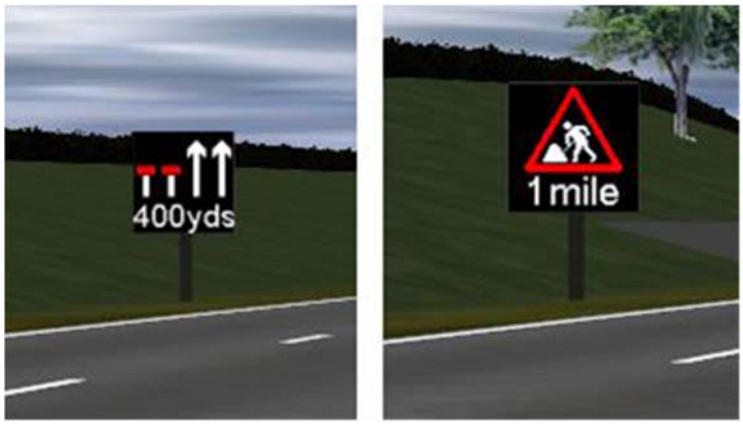


Figure 12. Shoulder mounted lane-use control signs being evaluated in a driving simulator study in England (*6*).

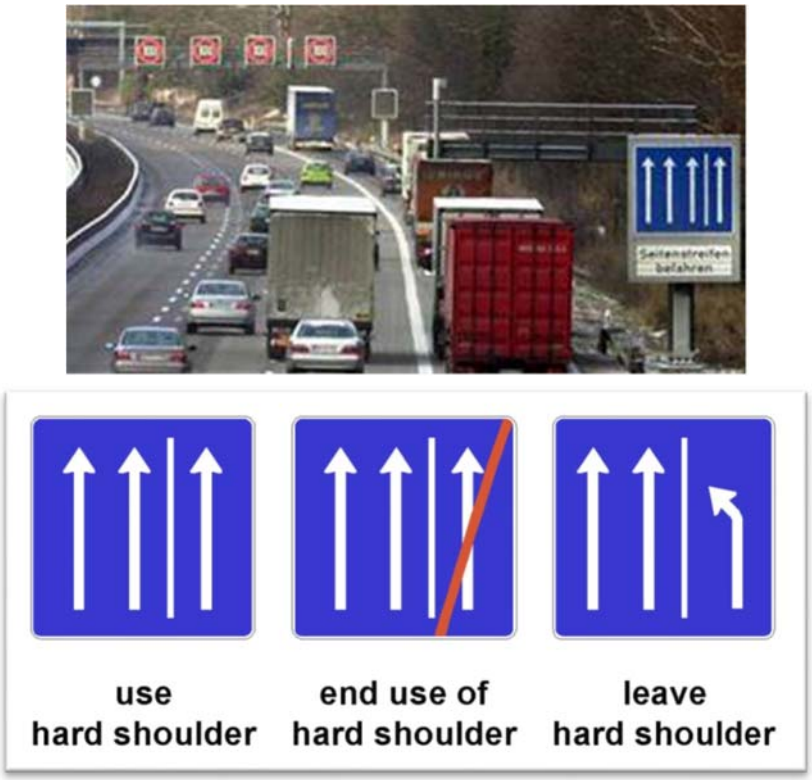


Figure 13. Shoulder mounted sign and library of messages used for hard shoulder running in Germany (*7*).

Seattle

The primary goal of the ATM signage deployment in the Seattle area is to reduce collisions by smoothing traffic flow under a variety of conditions, including incidents, congestion, and work zones. The Active Traffic Management Concept of Operations explores the goals, objectives, and needs that the ATM signage is intended to address (*8*). In the Seattle area, the ATM signage is actively managed 24 h every day. Additional staff was hired to handle the increased workload as the ATM deployments increased the number of electronic signs in the area from 60 to 300.

The ATM signs in the Seattle area are a blank screen by default and are used to show a variety of messages described below.

- The steady DOWNWARD GREEN ARROW is used during an incident scenario for open lanes that are unaffected by the incident.
- The RED X is used when lanes are closed, e.g., due to an incident or work zone activity.
- The steady DOWNWARD YELLOW ARROW with "CAUTION" (see example in Figure 14) is used in the right lane prior to an on-ramp merge containing heavy traffic, or if an incident or debris is encroaching into a lane without fully blocking the lane. The "CAUTION" portion of the message is experimental.
- A flashing YELLOW X to indicate the clearance interval or transition phase from shoulder-open to shoulder-closed.

- A left and/or right DOWNWARD DIAGONAL YELLOW ARROW is used in advance of a lane closure to inform motorists to vacate the lane for a closure ahead and is an experimental sign.
- Variable speed limits are white on black in the configuration of a typical speed limit sign.
- The white diamond is used to denote the high-occupancy vehicle (HOV) lane and whether it is active—"2+ ONLY" or "OPEN TO ALL"—during non-peak or an incident scenario.

Under normal operating conditions, while overhead ATM lane control signs are blank as a default, some overhead DMSs display travel times, and a few side-mounted DMS combinations in the corridor display a standard speed limit sign image (on both the left and right sides of the highway). Additionally, WSDOT has found value in using a steady DOWNWARD YELLOW ARROW display with the word CAUTION upstream of a ramp with heavy traffic or incident in the shoulder that is encroaching on the lane, as shown in Figure 14. As a result, operators now aggressively use this arrow display for congested ramp conditions, as applicable.

Source: Washington State Department of Transportation.

Figure 14. ATM signs displaying the caution arrow on I-90.

WSDOT has experimented with several response strategies in the event of a blocked lane. WSDOT personnel have noted that displaying the merge with DOWNWARD DIAGONAL YELLOW ARROW sign seems more effective than a YELLOW X with 1 MILE sign. Thus, the merge with diagonal arrow is the preferred strategy for a blocked lane. On the old pontoon bridge on SR 520, overhead sign structures were not possible so WSDOT used a YELLOW X with distance display of "1 MILE" or "2 MILE," as appropriate, if there is an incident on the bridge so that traffic will not preemptively merge, and thus reduce capacity. An example of this situation is shown in Figure 15. On the newly constructed floating bridge, they were able to install overhead sign gantries every 0.5 mile and these now show the DOWNWARD DIAGONAL YELLOW ARROW.

Source: Washington State Department of Transportation.

Figure 15. ATM signs on SR 520 pontoon bridge, circa 2010. These YELLOW Xs have now been replaced with DOWNWARD DIAGONAL YELLOW ARROWs for lane closure indications.

In the Seattle area, ATM signage displays regulatory variable speed limits. As shown in Figure 16, these signs are displayed in the configuration of a typical speed limit sign. Variable speed limits are entirely automated and are activated by the system in advance of congested areas, including those caused by incidents. However, operators can manually override the signs, if needed, to better reflect the current speed on the highway.

Source: Washington State Department of Transportation.

Figure 16. ATM signs displaying variable speed limits on I-5 northbound to downtown Seattle in 2012.

Minneapolis / St. Paul

Lane-use control signals have been used in the region for over 50 years on I-94 in advance of the Lowry Hill tunnel downtown Minneapolis. A reversible HOV lane section on I-394 from downtown to the western suburbs has also been in place for many years. Regional consistency in the use of the lane status symbols across these applications informed some of MnDOT's decisions for their ATM applications.

Deployment of ATM signage on the Interstate 35 West (I-35W) corridor began in September 2009 in Minneapolis with the inclusion of variable advisory speeds and lane status symbols. The variable speed system was discontinued in 2015 due to unreliability of speed data and latency leading to inaccurate speeds being posted.

The use of ATM signage is primarily for incident management and is expected to help reduce rear-end collisions and improve traffic flow. The 17-mi corridor contains 174 intelligent lane control signals at gantries spaced approximately every 0.5 mi. The location of the gantries was determined in large part by the fixed guide signs that were already in place, (e.g., overhead signs informing drivers of upcoming exits). When ATM signage was added, the guide signs were moved above the ATM signs. The left lane of the corridor for each direction is managed as a MnPass HOT lane during peak hours, in the peak direction of travel, open to carpools, buses, motorcycles, and MnPass users, and is used as a general-purpose lane otherwise, except the far northern section, which is open in the northbound direction only during peak hours as a Priced Dynamic Shoulder Lane (PDSL), as shown in Figure 17-Figure 19. A similar operation on I-94 between Minneapolis and St. Paul opened in 2012 and uses the same system.

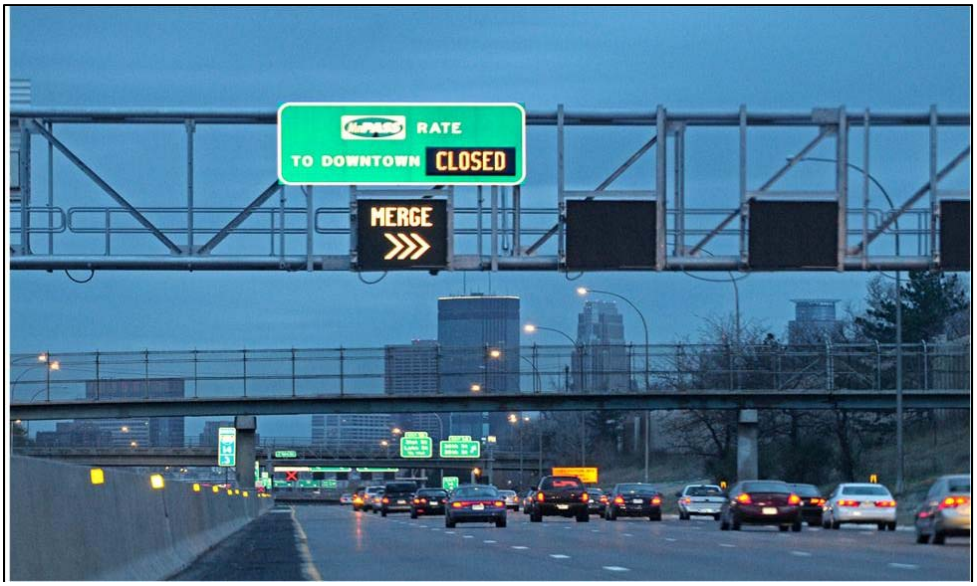
The ATM signs in Minnesota are a blank screen as a default but are used to show a variety of messages as described below. MnDOT has an active request for experimentation with FHWA for the use of the streaming chevron symbols on the merge message and the addition of distance information on the YELLOW X sign.

- The steady DOWNWARD GREEN ARROW is used when the PDSL is open. It is also used during an incident scenario for lanes that are unaffected by the incident.
- The RED X is used when lanes are closed due to an incident and when the PDSL is closed. This sign was modified after ATM deployment by adding the word "CLOSED" in an effort to better communicate its meaning to drivers. The "CLOSED" portion of the message is experimental.
- The flashing DOWNWARD YELLOW ARROW is used for lanes adjacent to an incident either in the next lane or on the shoulder. Motorists are allowed to use this lane but should use extreme caution. The flashing DOWNWARD YELLOW ARROW has been in the Minnesota MUTCD for nearly two decades for use outside the Lowry Tunnel on I-94 adjacent to downtown Minneapolis (*9*).
- The YELLOW X with "1 MILE" is used to alert motorists of a lane closure and merge ahead. The YELLOW X is never displayed without the distance, and 1 mi is the only distance ever displayed.
- Left or right sequential chevrons with "MERGE" are used to inform motorists to vacate the lane for a closure ahead (see example in Figure 19). This sign was based on the sequential chevron message currently permitted on arrow boards.

- Advisory speeds are amber on black since the variable speeds are advisory only. The sign could allow for regulatory black on white messages in the future.
- The white diamond is displayed to show when MnPass HOT lane restrictions are in place during peak periods (see Figure 18). This display is automatically posted during set peak hour times so that it can be used by the highway patrol to enforce the HOT restrictions.

Figure 17. I-35W ATM signage at PDSL section.

Figure 18. Variable speed limit on I-35-W in Minneapolis (photo Aug 2010).



Source: Minnesota Department of Transportation.

Figure 19. I-35W MnPASS and ATM signage with PDSL closed and merge display with sequential arrows.

MnDOT reports that the lane control signs on I-94 will be replaced in the summer of 2017 due to maintenance issues of the signs after the vendor stopped production. They will be replaced with 18 x 6 foot changeable message sign panels installed only every 1-2 miles that will display messages like RIGHT LANE CLOSED or use a pictogram displaying lanes with X and arrows. The signs will be smaller than a typical 30 foot wide full-sized changeable message sign used for incident management messages. MnDOT is interested in some of the shoulder-mounted lane status signs observed in the UK and Germany.

Northern Virginia

The Virginia Department of Transportation (VDOT) deployed an Active Traffic Management System (ATMS) on I-66 starting September 16, 2015. The system was implemented on 34 miles roadway along I-66 through Arlington, Fairfax, and Prince William counties from the Washington, D.C. line to Route 29 in Gainesville *(10)*. As part of the project, the 34-mile roadway was divided into five segments, with each segment outfitted with specific combinations of ATM strategies and technologies. These include lane control signal systems, shoulder lane management systems, adaptive ramp metering, enhanced detection and camera systems, queue warning systems, and others. These dynamic lane-use signs are employed around-the-clock, as needed – during both traditional peak periods and non-traditional times, including mid-day on weekdays and weekends.

The strategies and technologies considered in this system include *(10, 11)*:

- **Auxiliary lane control system** in terms of expanded use of the shoulder lanes between the Beltway and Route 50. The expanded treatment supports the use of the shoulder during high-volume periods, regardless of time of day, or if there is an incident blocking the lanes. The system uses signals above the lane to show either a

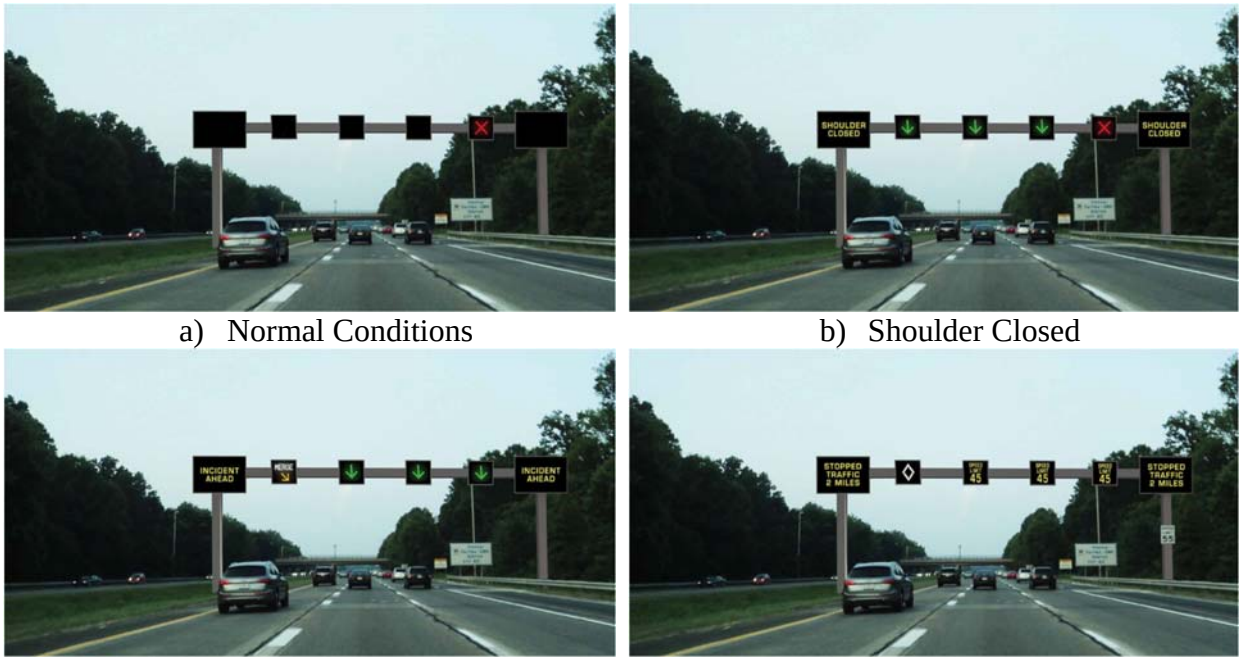
GREEN ARROW or RED X to indicate when the shoulder is open or closed to traffic. In past, the shoulder lanes were used only during weekday peak periods.

- **Dynamic lane control system** on all lanes between Nutley Street and Route 29 in Centreville. This treatment uses overhead gantries with lane control indicators over each travel lane to control traffic. Depending on circumstances, they show advisory speed limits, HOV lane restrictions, GREEN ARROWS, YELLOW ARROWS, or RED Xs to manage traffic. Figure 20 shows the dynamic lane control signs on I-66, the motorists are provided information on which lanes are usable or blocked well in advance of incidents.
- **Closed-circuit television (CCTV) cameras and dynamic message signs** between the District of Columbia and Route 29 in Gainesville. The cameras are used in monitoring of the highway and thus enabling transportation, safety, and law enforcement personnel to respond more quickly and appropriately to incidents. The dynamic message signs advise drivers of incidents and delays. Apart from lane control signs, the gantries also accommodate other devices such as CCTV, DMS, vehicle detectors, and queue warning system *(11, 12)*.
- **System-wide adaptive dynamic ramp metering.** This treatment provides ramp metering on I-66 at select, inside-the-Beltway on-ramps in order to regulate the flow of vehicles on to the highway. The ramp meters will be "adaptive," meaning that their timing will vary according to traffic conditions.

Figure 20. Dynamic lane control signal on I-66 (*10*).

Figure 21 (a) shows various lane control signal variations on I-66, in the normal conditions the signs are blank with a RED X over the shoulder showing that it is not operational and should not be used (*13*). Figure 21 (b) shows an instance when the shoulder is closed and should not be used, this is conveyed using the DMS on the gantry and RED X. Figure 21 (c) shows an instant when there is incidence downstream and the left lane is closed. In this picture, the traffic on the extreme left is being asked to merge to the right lane using diagonal merge arrow that points to the merging lanes because of incident downstream which is conveyed using

the DMS. The last picture (Figure 21 (d)) shows the availability of HOT lanes, reduced advisory speed on the general purpose lanes due to stopped traffic downstream, and the message on the DMS to explain the need of the reduced advisory speed. An informational video posted on VDOTs web page illustrates slightly different merge signs which apparently were never implemented (*12*, Figure 22).



a) Normal Conditions b) Shoulder Closed

c) Left Lane Closed Ahead d) Back of Queue Warning

Figure 21. Lane control sign variations on I-66 (*13*).

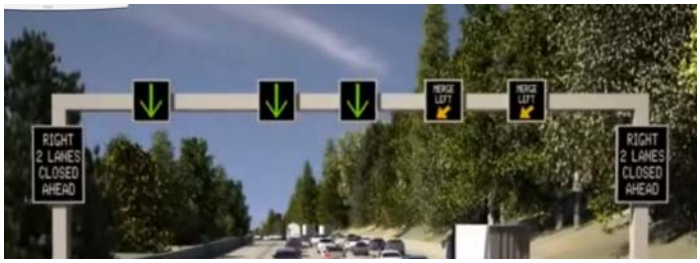


Figure 22. Screen image from July 2011 VDOT computer animation explaining I-66 operations (*12*). The text accompanying the merge message that was implemented on I-66 does not include the words left or right.

According to VDOT, the overhead lane signs and accompanying CMS panels located on the sign supports are expressly designed and positioned to promote readability and comprehensibility by travelers (*11*). Also, messages are repeated – so that if the drivers miss some or all of the information the first time, they can pick it up at the next set of signage.

The ATM treatments for specific segments were determined by studying the road usage patterns and crash data. Also, travelers' needs were identified and studied in each of the five roadway segments. VDOT is using a range of metrics to assess the success of the project

including travel time, travel time reliability, travel delay time, the length of travel delay queue, numbers of primary and secondary incidents, etc *(11)*.

Las Vegas

Project Neon in Las Vegas is the largest public works project in Nevada history. The project will widen 3.7 miles of I-15 between Sahara Avenue and the "Spaghetti Bowl" interchange in downtown Las Vegas. ATM could support construction activities during Project Neon implementation as well as support congestion management along the most important stretch of I-15 through the heart of Las Vegas beyond the completion of the project. A concept of operations (ConOps) study (*14*) was performed for the implementation of ATM strategies along this corridor. The goals for this Nevada Department of Transportation (NDOT) initiative in Las Vegas are to improve traffic flow and safety through the use of dynamic lane management, queue warning, and speed harmonization (variable speed limits). Within the corridor, NDOT plans to consider the use of strategies to improve merge control near the on-ramps to I-15 and US-95 as well as near the freeway-to-freeway interchange and to improve the operation of existing metered entrance ramps using adaptive and dynamic control strategies.

The ATM applications chosen by NDOT to implement for the Las Vegas I-15 freeway corridor were regulatory variable speed limits (speed harmonization), queue warning, dynamic lane merging (junction control), and dynamic ramp metering. Some ATM applications were not chosen to be implemented for this NDOT ATM system because of specific reasons, for instance, there are no adaptive ramp meters within the ATM project limits and no detection will be added to ramp meters in order to provide the adaptive capability. Similarly, there are no hard shoulders that are capable of handling the width or amount of traffic that travels on I-15 or US-95 general purpose lane within the ATM project limits, hence hard shoulder running was not considered.

According to the ConOps plan and confirmed at a 2017 presentation by project staff (*15*), the gantries will be provided at approximate 0.5 mile spacing. Each station (or "gantry") will differ slightly in quantities and content based on the number of lanes and the configuration. Each gantry location will provide 1,000 feet of clear visibility in advance of the gantry and a motorist will be able to see the next gantry while passing under the upstream gantry.

The lane control designations identified for this project are shown in Figure 23 and includes *(14)*:

- A <u>DOWNWARD GREEN ARROW</u> for notifying the traveler that the ATM system has been activated for a reason or that the traveler has passed the reason for ATM system activation and that the lane is open to travel.
- A <u>RED X</u> for a closed lane.
- <u>DOWNWARD DIAGONAL YELLOW ARROWs with MERGE</u> text will be used to allow traffic to move over one lane at a time in advance of a lane closure. This means that two merge arrows will not be offered at one gantry in advance of two lane closure because this would not allow proper time for traffic to move over two lanes away from the closed lanes.
- <u>Merge displays</u> will be displayed on upstream gantries consistent with the ability of traffic to merge over one lane at a time to merge away from the back of queue experiencing 35 mph or slower current operational speeds, or other user defined

threshold. Merge displays will only be used if current operational speeds are being detected below the user defined threshold.

- Merge left or right arrow display (two arrows on one display) will only be used if one or more of the middle lanes are closed that still offer a left or right lane merges over. This may include opening the HOV lane to all traffic as a merge over lane option for traffic.
- DOWNWARD DIAGONAL YELLOW ARROW (merge left arrow display or merge right arrow display) will not be allowed on the outer-most lane display signs. DOWNWARD DIAGONAL YELLOW ARROWs will only be used for lanes that offer a left or right lane to merge into. NDOT has determined that shoulder running will not be allowed as part of this ATM system management.

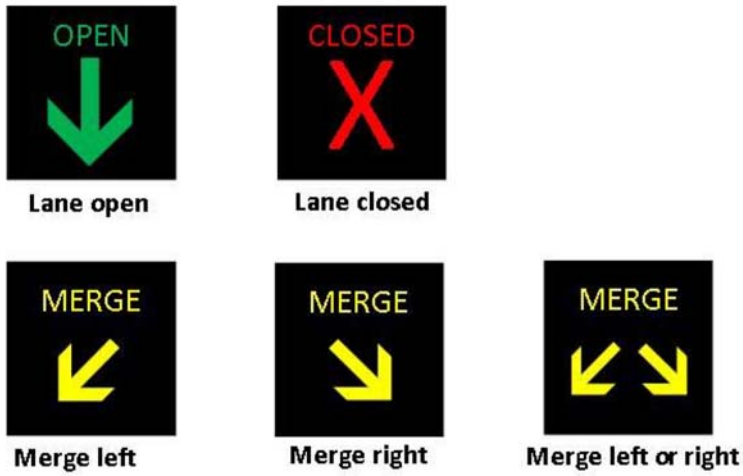


Figure 23.Dynamic Lane Use Control Signs Used for ATM in Las Vegas by NDOT (*14*).

For speed harmonization, the ConOps study suggests that the right pole displays will be limited to speed limit displays and supplemental messages beyond the information displays on gantries to indicate that speed harmonization is in effect or that the freeway has been closed. The speed limit display will include words “SPEED LIMIT” above the numerical value of the speed as shown in Figure 24. The left pole display will also be able to display speed limits as needed.

Caution message will be used only during queue warning messages provided on information displays in combination with speed limit one or more mile in advance of detected queuing traveling under 45 mph, in specific lanes upstream when no other lanes are being detected under 45 mph. An example of the caution message is provided in Figure 25. If speeds are being detected in more than one lane under 45 mph, the regulatory variable speed limit application will be activated.

During free flow conditions, a blank sign (no display) will be provided over the open general purpose lanes, HOV 2+ display will be active on the left pole display on the gantry, and the current speed limit of the roadway is provided on the right pole display on the gantry (*14*). Figure 24 shows the implementation of dynamic lane-use control signs for queue warning scenario presented in the ConOps study. The large CMS panel will span the entire width of the 5-lane freeway cross section and will include portions of the full-matrix sign dedicated to lane-use control symbols plus a 3-line message portion at the top center of the sign.

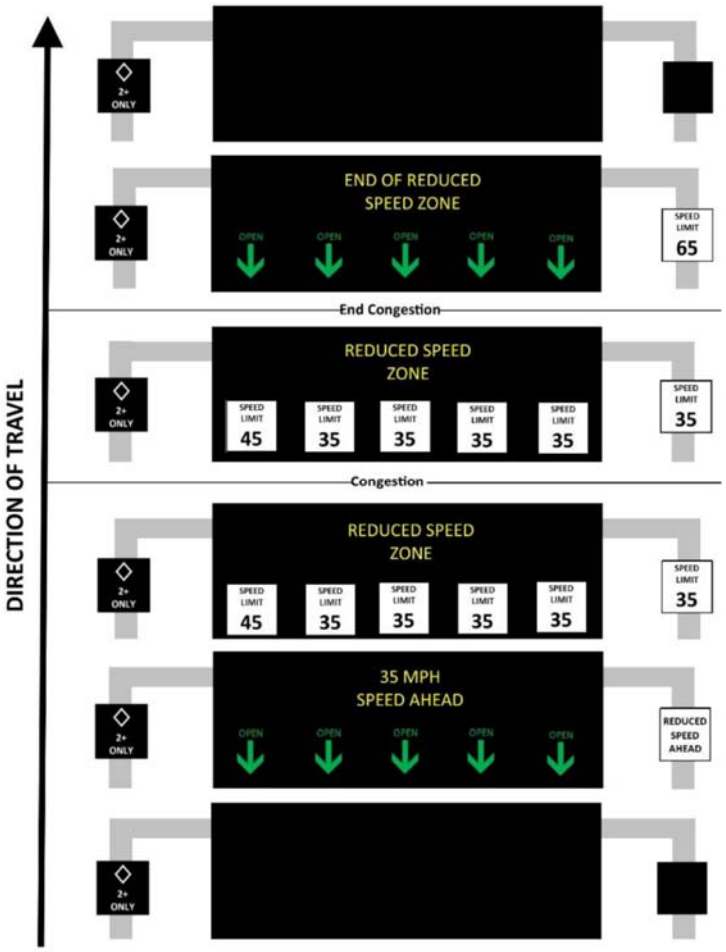
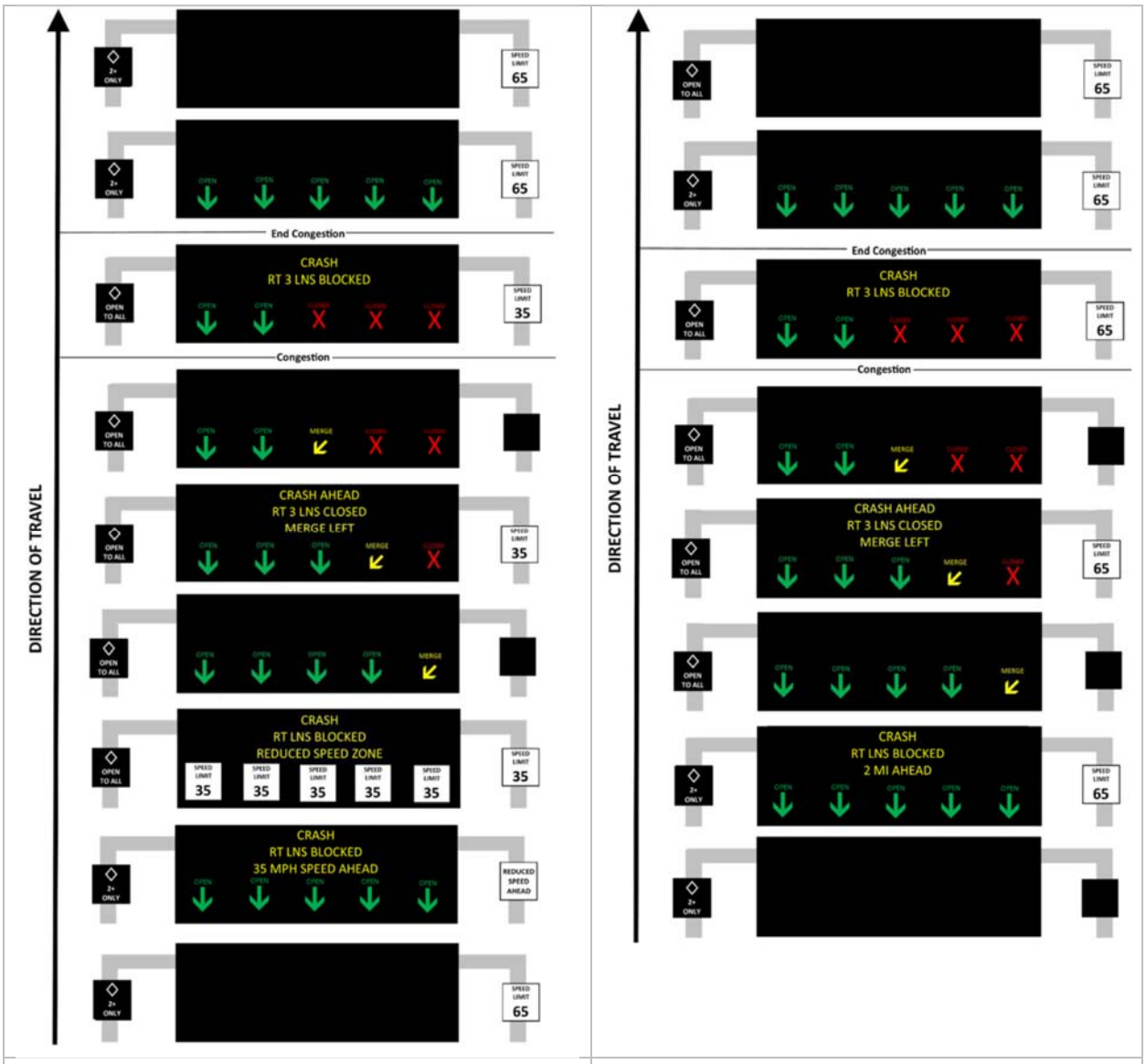


Figure 24. DLUC for Queue Warning Scenario at Las Vegas for ATM (*14*).

Figure 25. Queue Warning Caution Lane Display (*14*).

Figure 26 shows the application of DLUC in the incident scenario. Figure 26(a) shows the sequence of DLUC and the dynamic message signs for a crash blocking the right lanes during a congested condition. This also activates speed harmonization due to detected speeds lower than 45 mph (or other selected threshold). Hence, in this case, ATM not only assists in notifying users about closed right lane and merge in advance but also provides speed harmonization and queue warning leading up to the merging location away from the lane closed due to the crash. In a non-congested scenario, see Figure 26 (b), there is no speed harmonization. However in both cases, HOV restrictions are lifted (i.e., the HOV lane is opened to all traffic) in the area of the merge and closure process, returning to HOV 2+ beyond the crash site.

The ConOps document also details sign operation for planned closures for work zones or special events and dynamic junction control.



(a) Incident with Congestion Scenario **(b) Incident without Congestion Scenario**

Figure 26. Application of DLUC for Incident Scenarios with and without Congestion (*14*).

Chicago

The Illinois Tollway is planning a comprehensive dynamic lane control system on the Jane Addams Tollway (I-90) in the northwest Chicago area. This active traffic management system is expected to go live in spring 2017. There will be gantry every 0.5-mile between O'Hare International Airport and Barrington Road on I-90 (Jane Addams Tollway).

The objectives of ATM strategies on I-90 corridor are to:

- Safely route traffic during traffic incidents, particularly lane blocking events.

- Support transit bus service (PACE) use of left shoulder, during congestion in support of travel time reliability (*16*).
- Utilize variable advisory speeds to support safer vehicular flow near traffic congestion and incidents.

The feature of integrated transit creates the option for PACE buses to travel in the new Flex Lanes (inside lanes and shoulders) on I-90 to route around congestion and provide more reliable service (see Figure 27). The left shoulder sections will be opened to PACE when traffic congestion exceeds a threshold of congestion (30 percent of section is congested (< 35 MPH), parameters not final), and when the left shoulder is clear of incidents, debris, traffic stops, and maintenance activities *(17).*

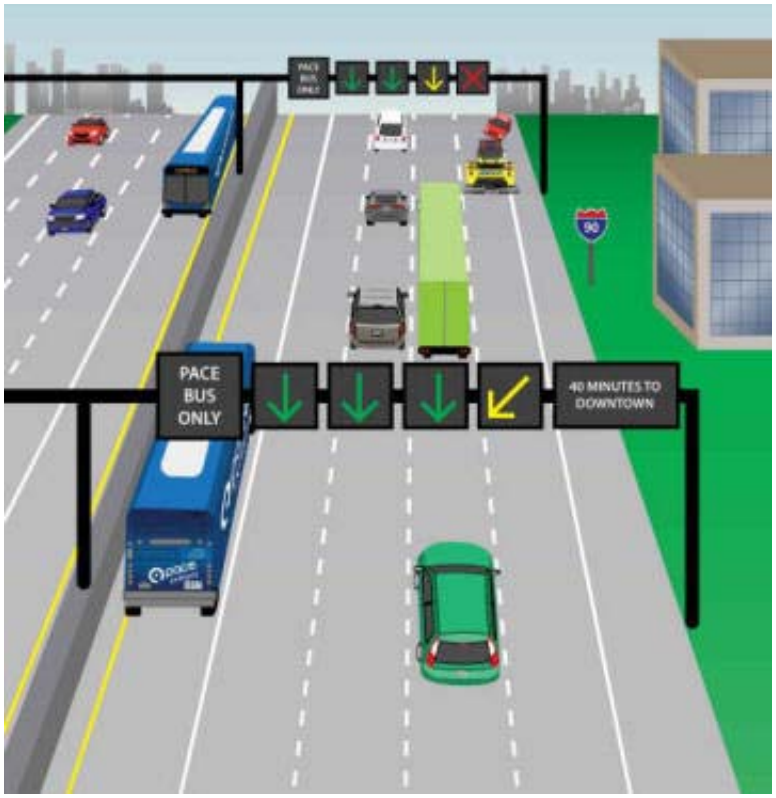


Figure 27. Integrated Transit on I-90 SmartRoad in Chicago, IL (*16*).

According to the technical memo, the RED Xs will be used on up to two gantries upstream of the lane closure location (*17*). More gantries could be used, but consideration for queue storage and driver compliance is based on two as the initial setting. The DOWNWARD DIAGONAL YELLOW ARROWs are supposed to direct traffic to open lanes upstream and adjacent to the RED Xs. The DOWNWARD YELLOW ARROWs will typically be used in support of Move Over/Scott's Law, on gantries nearest the traffic incident, with the objective of driver caution when directly adjacent to responders and all on-scene incident activities. Small DMS size (3 ft X 9 ft) will be installed on alternating gantries to provide extra information. Various scenarios have been studied in the tech memo. An example showing a center lane closure is illustrated in Figure 28. Note the use of DOWNWARD YELLOW ARROWs flanking the center lane closure to indicate drivers should use caution in these lanes.

Figure 28. Dynamic lane-use control sign configuration for center lane closure scenario proposed by the Illinois Tollway.

Atlanta

In the Atlanta region, the Georgia Department of Transportation has been operating a part-time shoulder running operation they have dubbed Flex Lanes on I-85 north and State Route 400. These have been operating on a fixed schedule with static signing indicating hours of operation. The I-85 North facility was updated to a dynamic operation and opened in December 2016. This is a short section of I-85 that operates as a part-time auxiliary lane between two major interchanges. They are using shoulder mounted cantilever signs with 3-foot CMS panels to indicate lane status. A ground mounted static sign is placed nearby to explain the meaning of the CMS symbols. The signs are placed 600-1200 feet apart along the 1 mile shoulder running section with a total of five signs in the section.

The Georgia DOT had intended to use an UPWARD DIAGONAL YELLOW ARROW as a transition phase between green and red when the lane was about to close. The UPWARD DIAGONAL YELLOW ARROW was proposed because it fits with principles of exit guide sign design in the MUTCD. After conferring with FHWA, they have not implemented this idea and the static sign shown in Figure 29 has been altered to cover the center line of text explaining the merge symbol. As of January 2017, the system is operating without a yellow phase though they expect to program one in the near future.

Figure 29. Norcross Georgia, I -85 N, Sept 2016. Start of shoulder lane, approximately 1000 feet north of Interchange with Jimmy Carter Blvd. Note, tolled express lane on left. The static sign has since been modified to have the center MERGE line covered by a plain white panel.

Summary of Effective Practices

The research team developed a spreadsheet to inventory DLUC operations on controlled access roadways in North America. Some of the information was obtain from phone conversations, other from published material, and some from unpublished material, for example interim reports to FHWA for an earlier project (*18*). The findings for lane-use controls are summarized in Table 3 for U.S. applications and in Table 4 for applications outside of the U.S. In order to group and compare operations, the team developed a set of operational characteristics to note for each facility. These serve as the columns in the spreadsheet tables and are:

- **Location**: Region, city, state, or country.
- **Route.**
- Lane Use Control Type:
    - **TS**: Standard traffic signal (two- or three-lenses traffic signal).
    - **LC**: Large CMS (approximately 4-foot square).
    - **SC**: Small CMS (approximately 2-foot square).
- Operation Objectives (i.e., what purpose is the device serving?)
    - **IM**: Incident management and maintenance (necessitating the closure of lanes).
    - **SH**: Speed harmonization.
    - **RC**: Confirmation of directionality for reversible/contraflow lanes.
    - **PS**: Part-time shoulder use.
- **Default**: Display state when inactive (Blank or Active, i.e. always displaying something, typically a green down arrow when operations are normal).
- **Spacing**: Longitudinal spacing frequency.
- **Other** comments – notes about specific location of signals, speeds, design features, etc.

Table 3. U.S. DLUC operations.

Location	Route	TS	LC	SC	IM	SH	RC	PS	Default	Spacing	Other Information or Comments
Jane Addams Tollway, Chicago, Illinois	I-94		X		X	X			Unknown	0.5 mile	Opens spring 2017
Minneapolis, Minnesota	I-35W		X			X		X	Blank	0.25-0.5 mile	w/ dynamic speed limits
Union City, New Jersey	Route 495			X	X		X		Active	0.25 mile	Inbound AM contraflow w/ dynamic speed limits (50 mph)
Inside lane HOV conversion, hard shoulder running, Virginia	I-66		X		X	X		X	Shoulder Active, Mainlanes Blank	Varies	Lane controls can display "merge" Supplemental static signs and shoulder painted.
I-5 Northbound, Seattle, Washington	I-5		X		X	X			Blank	Varies up to 1 mile, typically ½ mile	With dynamic speed limits
Atlanta, Georgia	I-85 N		X		X			x	RED X	varies	Cantilever sign only over right shoulder
I-15 and US-95, Las Vegas, Nevada	I-15 and US-95		X	X	X	X			Blank	0.5 mile	
Boulder Turnpike, Denver, Colorado	US 36		X		X	X			Blank	Varies	Added as part of managed lane project, 55mph
Eastbound Shoulder Lane, Colorado	I-70		X		X			X	Active	Unknown	Dynamic Flow Management / Metering

Where: TS=standard traffic signal (two- or three-lenses traffic signal), LC=large CMS (approximately 4 feet square), SC=small CMS (approximately 2 feet square), IM= incident management and maintenance (necessitating the closure of lanes), SH=speed harmonization, RC=confirmation of directionality for reversible/contraflow lanes, PS=part-time shoulder use.

Table 4. Outside of the U.S. DLUC operations.

Location	Route	TS	LC	SC	IM	SH	RC	PS	Default	Spacing	Other Information or Comments
The Netherlands (hard shoulder running)	A1, A2, A4, A6, A7, A9, A13, A27, A28, A50		X					X	unknown	600 m (1970 feet)	As of 2012, approximately 174 km deployed since 1996 with an additional 2 km planned expansion (*18*)
The Netherlands (Plus Lanes)	A1, A4, A12, A27, A28		X					X	unknown		As of 2012, approximately 116 km deployed since 1996 with an additional 65 km planned expansion (*18*)
United Kingdom (England)	M6, M40, M42		X		X	X		X	Blank	Under Review	Spacing is 500 m (1640 feet) & 800 m (2625 feet) on M42. As of 2012, approximately 40 km deployed since 1996, with an additional 400 km identified for potential hard shoulder running (*18*)
Germany	Autobahn (A) Routes: A3, A5, A7, A8, A99		X			X		X	unknown		As of 2012, approximately 250 km deployed since 1990s with an additional 150 km programmed (*18*)
France	A4-A86 joint section; A48 bus hard shoulder lane							X	unknown		As of 2012, approximately 12 km deployed (*18*)
Spain					X				unknown	500 m (1640 feet).	
Greece	Attiki Odos Toll Motorway	X							unknown		

Where: TS=standard traffic signal (two- or three-lenses traffic signal), LC=large CMS (approximately 4 feet square), SC=small CMS (approximately 2 feet square), IM= incident management and maintenance (necessitating the closure of lanes), SH=speed harmonization, RC=confirmation of directionality for reversible/contraflow lanes, PS=part-time shoulder use.

Differences in Operation Noted by Research Team

In completing the review of operational documents and speaking with operators, the research team noted a number of key differences in operation. These topics will be addressed further through the research activities of the project.

Default State of Signal

Almost all bridge and tunnel applications maintain color or arrow functionality 24/7, while some mainline lane controls become inactive (i.e., blanked out) outside peak demand periods and when there are no incidents/maintenance conditions that justify their use. Arterial and freeway reversible lane applications allow for signs to be darkened when not in use.

Surveys of drivers regarding changeable message signs have demonstrated that most drivers believe the sign has malfunctioned when they see a blank sign (*19*).

Symbol Used in Transition Phase from Open to Closed

Lane status needs to change from open to closed after an incident is cleared or when a shoulder-running period is ending. Similar to a clearance interval at a signalized intersection, agencies feel that a sudden transition from green phase to red phase may cause drivers to attempt sudden merges. A signal indication or sign message that conveys this transition period was expressed as a need by several agencies interviewed.

Merge Symbol

Agencies differed on the CMS message (or signal indication) used to communicate the message “vacate the lane”. The MUTCD dictates that steady YELLOW X serves this purpose, but most international operations use a DOWNWARD DIAGONAL YELLOW ARROW for this purpose. This practice has been adopted by several U.S. operations either alone or paired with the MERGE text. Other agencies borrow from work zone arrow board operations and use a sequential chevron message. This area has been the topic of several research studies.

End of Queue Warning

The MUTCD does not provide a lane-use control signal indication to address the message “lane is open, but slow down and proceed with caution”. This message content is a key operational goal for many ATM applications. Some agencies are using an advisory speed limit to communicate this message while other use some form of a caution message either in text or with a DOWNWARD YELLOW ARROW.

Supplemental Explanatory Signs

Several agencies reviewed use supplemental static signs to explain the lane-use control signal indications in the vicinity of the overhead gantries (see example in Figure 30). This is the practice in several international operations reviewed as well.

Figure 30. Supplemental sign used along I-66 corridor to explain dynamic lane-use signal indications (photo courtesy of VDOT).

Appendix: Sections of the Manual on Uniform Traffic Control Devices

The 2009 MUTCD contains information on lane-use control signals and related changeable message signs in these general areas:

- Chapter 4M Lane-Use Control Signals in *Part IV Highway Traffic Signals.*
- Chapter 2L Changeable Message Signs in *Part II Signs.*
- Chapter 4K. Highway Traffic signals at Toll Plazas, Section 4K.02 *Part IV Highway Traffic Signals.*
- Section 2B.26 Reversible Lane Control Signs in *Part II Signs.*
- Section 2G. Preferential Lane Regulatory Signs in *Part II Signs.*
- Section 6F.61 Arrow Boards in *Part VI Temporary Traffic Control*.

Chapter 4M Lane-Use Control Signals in Part IV Highway Traffic Signals

The main location where Lane-Use Control Signals are defined is in the Signals Chapter 4M. This section was developed to support reversible lane applications on freeways and arterials and has been in this section through several editions of the MUTCD. The introductory material used in Section 4M.01 reflects that the material was written prior to freeway ATM operations. The option statement, however, does hint at incident management (Option C) and dynamic junction control operations (Option A).

Section 4M.01 Application of Lane-Use Control Signals
Support:
01 Lane-use control signals are special overhead signals that permit or prohibit the use of specific lanes of a street or highway or that indicate the impending prohibition of their use. Lane-use control signals are distinguished by placement of special signal faces over a certain lane or lanes of the roadway and by their distinctive shapes and symbols. Supplementary signs are sometimes used to explain their meaning and intent.

02 Lane-use control signals are most commonly used for reversible-lane control, but are also used in certain non-reversible lane applications and for toll plaza lanes (see Section 4K.02).

Option:
05 Lane-use control signals may also be used if there is no intent or need to reverse lanes, but there is a need to indicate the open or closed status of one or more lanes, such as:
A. On a freeway, if it is desired to close certain lanes at certain hours to facilitate the merging of traffic from a ramp or other freeway;
B. On a freeway, near its terminus, to indicate a lane that ends;
C. On a freeway or long bridge, to indicate that a lane may be temporarily blocked by a crash, breakdown, construction or maintenance activities, or similar temporary conditions; and
D. On a conventional road or driveway, at access or egress points to or from a facility, such as a parking garage, where one or more lanes of the access or egress are opened or closed at various times.

Section 4M.02 provides definitions of the signal indications used on DLUC signals. Only the items relevant to ATM applications are summarized in Table 5. The other indications are for white turn arrow used in arterial applications.

Table 5. MUTCD meanings of lane-use control signal indications (Section 4M.02).

Steady DOWNWARD GREEN ARROW	A road user is permitted to drive in the lane over which the arrow signal indication is located.
Steady YELLOW X	A road user is to prepare to vacate the lane over which the signal indication is located because a lane control change is being made to a steady RED X signal indication.
Steady RED X	A road user is not permitted to use the lane over which the signal indication is located and that this signal indication shall modify accordingly the meaning of other traffic controls present.

Section 4M.03 provides details on the design and visibility of the signal indications and was summarized earlier in this report in the section on lane-use control signal hardware.

Section 4M.04 provides standards and guidance on the operation of lane-use control signals. Most of this section is specific to reversible lane operations. Two standard statements, however, apply to freeway ATM operations as well. Standard 3 addresses the transition phase from green to red and allows for a YELLOW X transition or an immediate change to RED X.

03 **A moving condition in one direction shall be terminated either by the immediate display of a RED X signal indication or by a YELLOW X signal indication followed by a RED X signal indication. In either case, the duration of the RED X signal indication shall be sufficient to allow clearance of the lane before any moving condition is allowed in the opposing direction.**

Standard 7 addresses the resting state of the signal indications and allows for blanking the signs when not in operation. This is one operational feature that the research team found varied across the operations reviewed.

07 **If used, lane-use control signals shall be operated continuously, except that lane-use control signals that are used only for special events or other infrequent occurrences and lane-use control signals on non-reversible freeway lanes shall be permitted to be darkened when not in operation. The change from normal operation to non-operation shall occur only when the lane-use control signals display signal indications that are appropriate for the lane use that applies when the signals are not operated. The lane-use control signals shall display signal indications that are appropriate for the existing lane use when changed from non-operation to normal operations. Also, traffic control devices shall clearly indicate the proper lane use when the lane control signals are not in operation.**

Chapter 2L Changeable Message Signs in Part II Signs

The 2009 MUTCD does list lane control as one application of CMS (Section 2L.02). Chapter 2L on CMS addresses in a very broad way all issues related to CMS: message content, legibility, design characteristics, message length, and installation of permanent CMS. The design characteristics described in Section 2L.04 prohibit any animation, scrolling or dynamic elements. At least one operation reviewed by the research team includes sequential chevrons (i.e. >>>) to indicate a merge message.

This chapter does address changeable lane-use signs, but the text is really referring to old-fashioned open/closed signs for weigh stations or blank-out signs used for turn lane restrictions.

2L.01 *Guidance:*
05 *Blank-out signs that display only single-phase, predetermined electronic-display legends that are limited by their composition and arrangement of pixels or other illuminated forms in a fixed arrangement (such as a blank-out sign indicating a part-time turn prohibition, a blank-out or changeable lane-use sign, or a changeable OPEN/CLOSED sign for a weigh station) should comply with the provisions of the applicable Section for the specific type of sign, provided that the letter forms, symbols, and other legend elements are duplicates of the static messages as detailed in the "Standard Highway Signs and Markings" book (see Section 1A.11). Because such a sign is effectively an illuminated version of a static sign, the size of its legend elements, the overall size of its legend elements, the overall size of the sign,*
and placement of the sign should comply with the applicable provisions for the static version of the sign.

Chapter 4K. Highway Traffic signals at Toll Plazas, Section 4K.02 Part IV Highway Traffic Signals

Section 4K specifies lane-use control signals used over toll plaza lanes that are sometimes closed to traffic. A reference to Part 6 (Temporary Traffic Control) is made in this chapter describing situations where other lane closure devices may be used to close an Open Road ETC (Electronic Toll Collection) lane.

> 04 Lane-use control signals may also be used to indicate the open or closed status of an Open-Road ETC lane as a supplement to other devices used for the temporary closure of a lane (see Part 6).

Section 2B.26 Reversible Lane Control Signs in Part II Signs

Section 2B.26 addresses supplemental static signs used in conjunction with reversible lane control signals such as the one shown in Figure 31. These signs serve an educational purpose to explain the symbol indications on the signal faces. This section also provides guidance on the use of flashing beacons to "accentuate" the overhead lane-use control signals. Similar supplemental explanatory signs have been used by several of the agencies with dynamic lane-use freeway ATM operations.

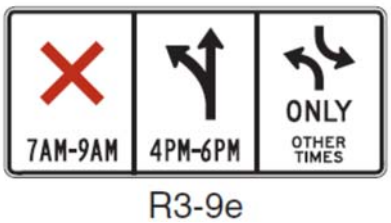


Figure 31. Regulatory sign to accompany arterial reversible lane flow operations (MUTCD Figure 2B-7).

Section 2G. Preferential Lane Regulatory Signs

The Red X and Green down-arrow used by all U.S. operations to indicate lane open/closed status was derived from guidance for reversible flow HOV lanes found in Section 2G. Though not illustrated in Section 2G, presumably a YELLOW X transition phase on these signs would be allowable because this section references Chapter 4M (Section 2G.05 sub-section 18).

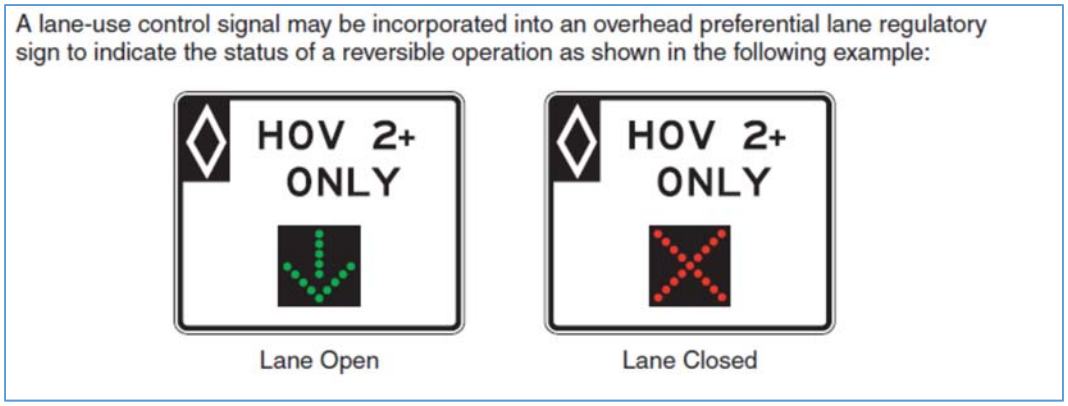


Figure 32. Preferential lane regulatory signs and plaques (MUTCD Figure 2G-1 Sheet 2).

Section 6F.61 Arrow Boards in Part VI Temporary Traffic Control

Section 6F addresses design and operation of arrow boards for temporary traffic control. The research team has included this material because incident management is a key operation for dynamic lane-use control devices in ATM applications. The messages used on arrow boards should be considered as one of the principles at work in the MUTCD. Drivers encounter arrow boards communicating caution and merge messages routinely (see Figure 33). The MnDOT practice of using streaming, sequential chevrons was derived from arrow board applications.

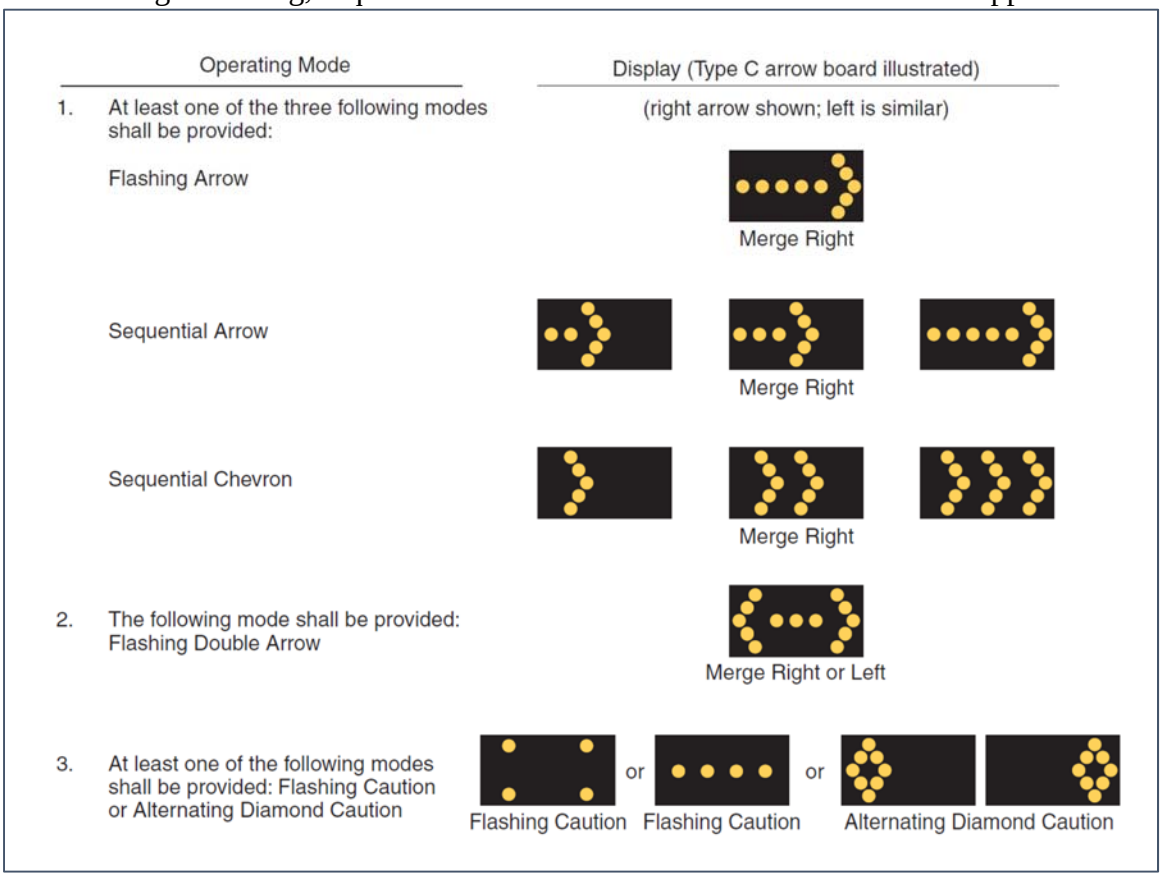


Figure 33. Advance warning arrow board display specifications (MUTCD Figure 6F-6).

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