UTCM

Improving the Quality of Life by Enhancing Mobility

University Transportation Center for Mobility

DOT Grant No. DTRT06-G-0044

General Guidelines for Active Traffic Management Deployment

Project Title: Best Practices and Outreach for Active Traffic Management

Interim Report

Charles Levecq, Beverly Kuhn, and Debbie Jasek

Performing Organization
University Transportation Center for Mobility™
Texas Transportation Institute
The Texas A&M University System
College Station, TX

Sponsoring Agency
Department of Transportation
Research and Innovative Technology Administration
Washington, DC

Texas Transportation Institute

UTCM Project #10-01-54
October 2011

Technical Report Documentation Page

1. Report No. UTCM 10-01-54-1	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle General Guidelines for Active Traffic Management Deployment		5. Report Date August 2011
		6. Performing Organization Code Texas Transportation Institute
7. Author(s) Charles Levecq, Beverly Kuhn, and Debbie Jasek		8. Performing Organization Report No. UTCM 10-01-54-1
9. Performing Organization Name and Address University Transportation Center for Mobility™ Texas Transportation Institute The Texas A&M University System 3135 TAMU College Station, TX 77843-3135		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. DTRT06-G-0044
12. Sponsoring Agency Name and Address Department of Transportation Research and Innovative Technology Administration 400 7th Street, SW Washington, DC 20590		13. Type of Report and Period Covered Final Report January 2010–April 2011
		14. Sponsoring Agency Code
15. Supplementary Notes Supported by a grant from the US Department of Transportation, University Transportation Centers Program		

16. Abstract

Continued growth in travel in congested freeway corridors and limited public funding for expansion and improvement projects are limiting agencies' abilities to provide sufficient roadway capacity in major metropolitan areas. Focusing on trip reliability, active traffic management (ATM)—widely deployed for decades in Europe but in its early stages in the United States—maximizes the effectiveness and efficiency of the facility, and increases throughput and safety through integrated systems with new technology, including the automation of dynamic deployment to optimize performance quickly. This congestion management approach consists of a combination of strategies that, when implemented in concert, fully optimize the existing infrastructure and provide measurable benefits to the transportation network and the motoring public. These strategies include speed harmonization, temporary shoulder use, junction control, and dynamic signing and re-routing. By providing transportation agencies across the United States with crucial information on best practices for deployment and operation of ATM strategies, this project can have a positive impact on transportation networks were ATM is deployed. This document provides an overview of practices to date in ATM deployment as well as general guidelines that can help facilitate ATM implementation.

17. Key Words Active Traffic Management, Congestion, Transportation Operations, Safety, Freeway Management		18. Distribution Statement Public distribution	
19. Security Classif.(of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 47	22. Price n/a

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

General Guidelines for Active Traffic Management Deployment

by

Charles Levecq
Graduate Research Assistant
Texas Transportation Institute

Beverly Kuhn, P.E., Ph.D.
Senior Research Engineer
Texas Transportation Institute

and

Debbie Jasek
Research Specialist
Texas Transportation Institute

Project Title: Best Practices and Outreach for Active Traffic Management

August 2011

University Transportation Center for Mobility™
Texas Transportation Institute
The Texas A&M University System
College Station, TX 77843-3135

UTCM
University Transportation Center for Mobility™
Texas Transportation Institute

Texas Transportation Institute

U.S. Department of Transportation
Federal Highway Administration

Disclaimer

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. This document is disseminated under the sponsorship of the Department of Transportation, University Transportation Centers Program in the interest of information exchange. The U.S. Government assumes no liability for the contents or use thereof.

Acknowledgments

This document was completed as part of a project conducted in cooperation with the funding and staff from the University Transportation Center for Mobility™. The authors appreciate their guidance and support throughout the project. Special thanks are also extended to those international and domestic agencies for their participation in case study interviews.

Table of Contents

List of Figures

NOTE: Color figures in this report may not be legible if printed in black and white. A color PDF copy of this report may be accessed via the UTCM website at http://utcm.tamu.edu, the Texas Transportation Institute website at http://tti.tamu.edu, or the Transportation Research Board's TRID database at http://trid.trb.org.

List of Tables

Executive Summary

Since the 1980s, European countries have evaluated the effectiveness of measures designed to increase capacity and safety on motorways without having to widen them. These measures—called active traffic management (ATM)—include shoulder use, speed harmonization, queue warning, dynamic merge control, dynamic rerouting, and dynamic truck restrictions. ATM strategies can have a positive impact on transportation in the United States. This project contains crucial information on best practices for deployment and operation of ATM strategies.

Shoulder use for all vehicles allows all drivers to use the designated shoulder when open. Traffic control devices over or adjacent to the shoulder instruct drivers when driving on the shoulder is permitted. Transit-only shoulder use allows only transit vehicles to use the designated shoulder under specific conditions and driving regulations.

Many countries and several states in the United States deploy speed harmonization for weather-related conditions and congestion management. Speed harmonization is an operational strategy where agencies use an expert system to monitor data coming from field-deployed sensors on a roadway and proactively and automatically adjust speed limits when congestion thresholds are exceeded and congestion and queue formation are imminent.

Based on dynamic traffic detection, queue warning informs travelers of the presence of upstream queues, using warning signs and flashing lights. This strategy allows the traveler to anticipate a situation of emergency braking and limit the extent of speed differentials, erratic behavior, and queuing-related collisions.

Dynamic merge control closes specific lanes upstream of the interchange to manage access based on traffic demand. A typical U.S. application is a lane drop for one of the outside lanes or a merging of two inside lanes, both of which are static solutions. The intent is to provide dynamic priority access to the higher traffic stream.

Dynamic rerouting and traveler information consist of redirecting traffic to avoid unequal levels of service on parallel routes, providing users with viable route alternatives and helping reduce the impact of noncurrent congestion. A new direction can be suggested by dynamic message sign while the standard routing remains, or if the hardware allows it, the standard routing may be substituted by the recommended one.

Dynamic truck restrictions require all truck traffic to use designated lanes during peak periods. The intent is to increase the homogeneity of speed on each lane and to minimize the disruption in traffic flow caused by heavy vehicles.

ATM has the potential to help transportation agencies operate existing facilities in the most efficient manner possible. Potential improvements can include:

- An increase in average throughput for congested periods;
- An increase in overall capacity;
- A decrease in primary accidents;
- A decrease in secondary accidents;

- A decrease in accident severity;
- An overall harmonization of speeds during congested periods;
- An increase in trip reliability; and
- The ability to delay the onset of freeway breakdown.

Chapter 1: Background

Document Overview

A 2006 FHWA sponsored International Scan Tour of Europe examined the congestion management programs, policies, and experiences of other countries that are either in the planning stages, have been implemented, or are operating on freeway facilities. This scan sought information on how agencies approach highway congestion and how they are planning for and designing managed lanes at the system, corridor, and project or facility level. The scan tour revealed a complete package of strategies that make up the broader concept of active traffic management (ATM). This approach to congestion management is more holistic and is considered the next step in congestion management of freeway corridors. The FHWA scan tour defined active traffic management as the ability to dynamically manage recurrent and non-recurrent congestion based on prevailing traffic conditions (*1*). Similarly, the Transportation Research Board Joint Subcommittee on ATM defines it as the ability to dynamically manage traffic flow based on prevailing traffic conditions (*2*). Focusing on trip reliability, its goal is to maximize the effectiveness and efficiency of the facility under both recurring and non-recurring congestion as well as during capacity reductions involving incidents or road work. Through the flexible use of the roadway, ATM aims to increase system performance as well as traveler throughput and safety through the use of strategies that actively regulate the flow of traffic on a facility. ATM strategies can be automated, combined, and integrated to fully optimize the existing infrastructure and provide measurable benefits to the transportation network and the motoring public. These strategies include but are not limited to speed harmonization, temporary shoulder use, junction control, queue warning, ramp metering, lane restrictions, and dynamic rerouting and traveler information.

ATM is virtually in its infancy in the United States when compared to Europe. Only a handful of states have deployed some type of ATM strategy, and agencies are challenged with finding good guidance on deployment alternatives.

Scope, Purpose, and Intended Audiences

This document provides general high-level guidelines for successful ATM deployment based on international and domestic experience. It is envisioned that state DOTs and their partnering agencies—including metropolitan planning organizations (MPOs), transit authorities, commuter organizations, toll authorities, and regional mobility authorities—will have an interest in the results in assessing the best approach for ATM deployment in their region.

Chapter Summary

The following chapters are included in this report:

- **Chapter 1—Background:** Provides a background, scope, and purpose of the report, identifies the intended audiences and uses for the document, and gives a summary of the report components.
- **Chapter 2—ATM Experience:** Details a comprehensive overview of experience with active traffic management, both internationally and domestically.

- **Chapter 3—Best Practices and Guidelines:** Details the development of guidelines for successful ATM deployment based on the results of a literature review and assessment of ATM experience that transportation professionals can use to identify the most appropriate ATM strategy for their jurisdiction.
- **Chapter 4—Final Remarks:** Provides a final comment on the document for readers.

Chapter 2: ATM Experience

Traffic congestion is a problem found in industrialized countries worldwide, and every year the congestion problems grow. Since the 1980s, European countries, including Germany and the Netherlands, have started to evaluate the effectiveness of measures designed to increase capacity and safety on motorways without having to widen them. These measures include shoulder use, speed harmonization, queue warning, dynamic merge control, dynamic rerouting, and dynamic truck restrictions. All of these measures are grouped under one general name: Active Traffic Management.

ATM has proven effective in reducing congestion while requiring little to no geometric changes in the facilities. As explained later in detail, these measures can prove very efficient in managing congestion and safety on highways in the United States.

Shoulder Use

Shoulder use, also known as hard shoulder running (HSR), is a measure designed to temporarily increase the capacity of a facility by opening one or sometimes both shoulders to traffic. In some instances, only transit buses are allowed to use the shoulder lane. This section of the report investigates different shoulder use practices in both European countries and the United States.

Shoulder Use in England

In England, the Highways Agency implemented shoulder use on M42 as part of the pilot project for multiple traffic management measures including speed harmonization with camera enforcement, incident detection with queue warning, and traveler information (*3*). Temporary shoulder use is controlled by the traffic management center and is exclusively applied between exits, making the shoulder operate like an auxiliary weaving lane. Enforcement is performed through a wide network of cameras with automatic number plate recognition. Loop detectors placed every 100 m in all lanes, including the shoulder, provide additional traffic data. The striping pattern for the shoulders on M42 is the same as that for a regular motorway without temporary shoulder use: a continuous line separating the shoulder from the other lanes. To avoid surprising drivers that enter the shoulder, the rumble strips that induce noise in the vehicle was reduced, and raised pavement markers were placed on both sides of the shoulder lane. Extra emergency refuge areas are placed at regular intervals (every 500 m on the M42) to ensure safety for vehicles in distress during shoulder operation. Each refuge area is also equipped with loop detectors to elicit a quick response by the control center (3, *4*).

Overhead lane control signals are used to implement temporary shoulder use. When the shoulder is meant for emergency purposes only, a red cross is shown in the sign above the shoulder while the other overhead signs are either blank (under normal conditions) or display a mandatory speed limit (under congested or incident conditions). When the shoulder is open to traffic, the mandatory speed limit is displayed on the shoulder overhead sign and a description of the situation is written on a dynamic message sign (DMS)—typically "Congestion, Use hard shoulder" as pictured in Figure 1. These lane control signals can also prove very useful during incidents to clear one lane and provide quicker access for emergency vehicles. The pilot project included other features that were added to the motorway including lighting and emergency phones at every emergency refuge area.

The Highways Agency expected that shoulder use alone would reduce the initial level of safety; therefore, a safety plan was assembled for the project. Each hazard that was found had a risk assessment and a mitigation plan implemented if necessary (3). According to a feasibility study by the British Department for Transport, data showed that safety was not reduced during the time the temporary shoulder use had been in place; in fact, the tendency pointed to an improvement (*5*).

Figure 1. Example of operations under speed harmonization without shoulder use (left) and with shoulder use (right) (3).

The environmental impacts of implementing shoulder use are expected to be far lower than adding a new lane. Less construction is needed, especially if the shoulder pavement thickness is sufficient. Furthermore, loop detectors are already present on the entire motorway and the shoulder. The need for right-of-way is also reduced. The improvement in quality of flow reduces congestion and emissions per vehicle. However, the shoulder use might increase total emissions because of the added capacity. It was recommended that if shoulder use is to be implemented on a wide scale, driver education and communication are necessary, with particular attention being paid to optimizing the efficiency and safety on the motorway (*6*).

The results of the M42 pilot project included a travel time decrease of 26 percent in the northbound direction and 9 percent in the southbound direction. Also, travel time reliability increased by 27 percent in the northbound direction and 34 percent in the southbound direction

(5). Additionally, the M42 was able to carry significantly more vehicles. The before and after daily flow profiles are shown in Figure 2. During both peak periods, significantly more vehicles can use the M42 with 4-lane operations (3 lanes plus shoulder) compared to the original 3-lane operation. In both cases, speed harmonization (variable mandatory speed limits [VMSL]) was available to further manage traffic (*7*).

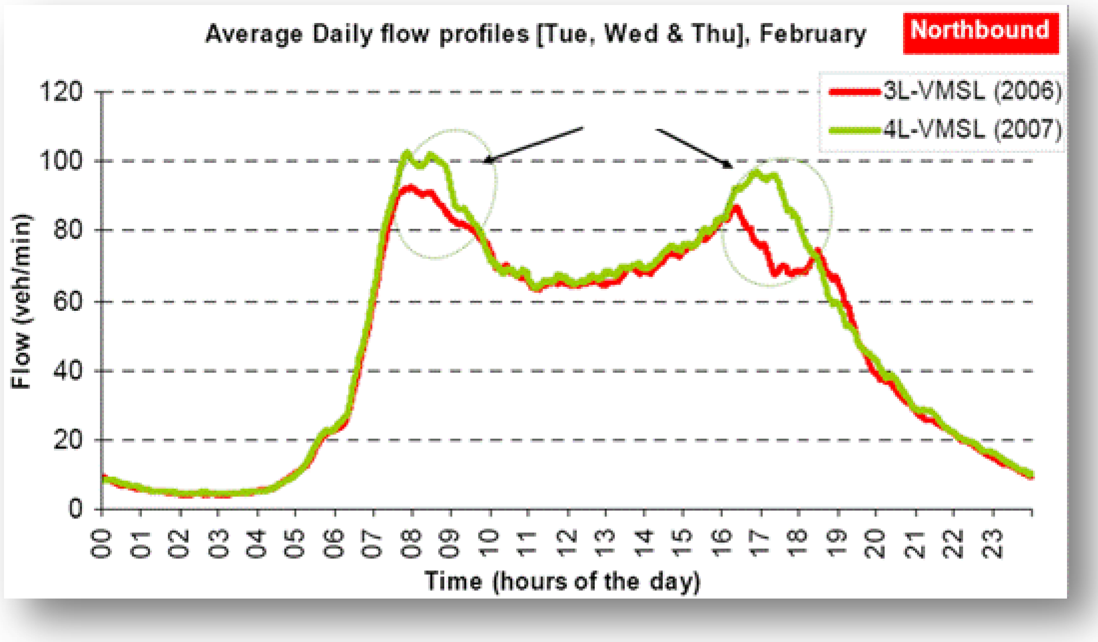

Figure 2. Before and after average daily flow profiles with and without shoulder use (7).

The cost of the M42 project was £5.6 million per km (£96.4 m total). Added to these costs is the cost of communication on the pilot program of £300,000 (plus VAT). In comparison, adding an extra lane in each direction would have had an estimated cost between £18 million and £25 million per km for a total of approximately £370 million (7).

Shoulder Use in Germany

In Germany, transportation agencies can use one of two ways to turn the right shoulder into a usable lane: they can restripe the shoulder as another lane with a broken line on the left side and a solid line on right side or, more commonly, they can stripe the shoulder lane with solid lines on both sides (*8*). Shoulder use is controlled by the state traffic center. When traffic volumes reach a trigger value established by traffic center personnel, the system suggests enabling shoulder use. An operator then checks the shoulder for obstacles using field cameras. If the shoulder is clear, the operator can allow traffic to use the shoulder. If an obstacle were to be detected later, the use of the shoulder would be stopped immediately (*9*).

The improvement in terms of added capacity is made obvious in the speed-volume diagram shown in Figure 3. It also shows the point at approximately 2,700 vehicles per hour (vph) at which shoulder use should be enabled (8).

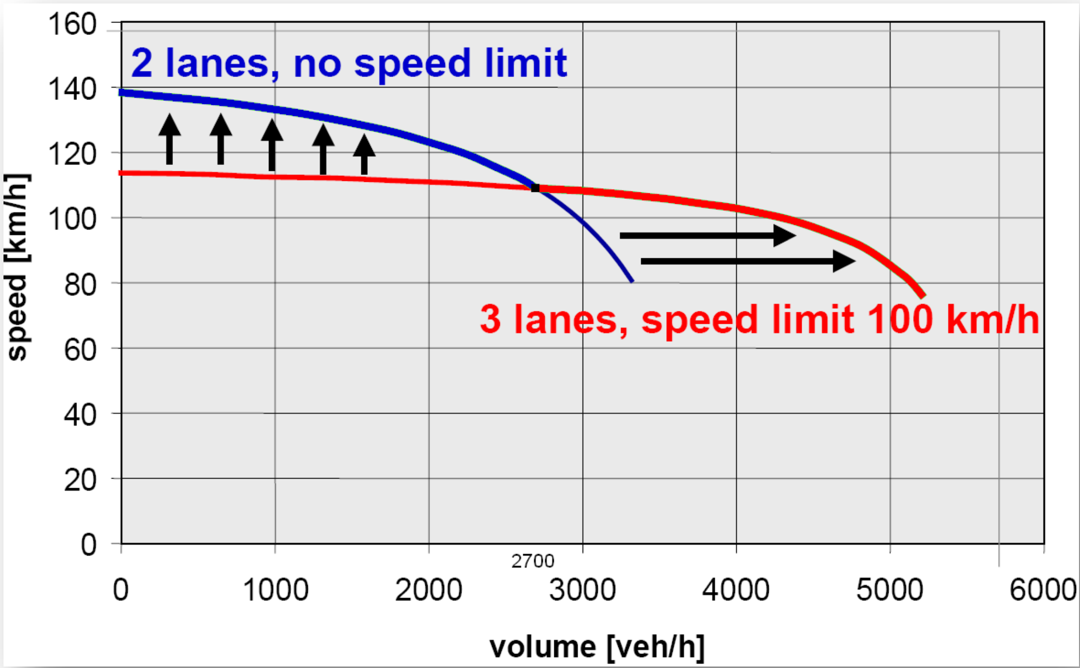

Figure 3. Speed/flow curves corresponding to both states of shoulder use (8).

The signing for shoulder running is usually a ground mounted rotating sign. As shown in Figure 4, the sign has three faces with the following text: use hard shoulder, end use of hard shoulder, and leave hard shoulder. When shoulder use is active, a lower speed limit is also set for safety. When shoulder use is inactive, these signs are blank. The usual speed on the motorway is 120 km/h, and the maximum speed allowed is 100 km/h when shoulder use is active, as seen in Figure 5 (8).

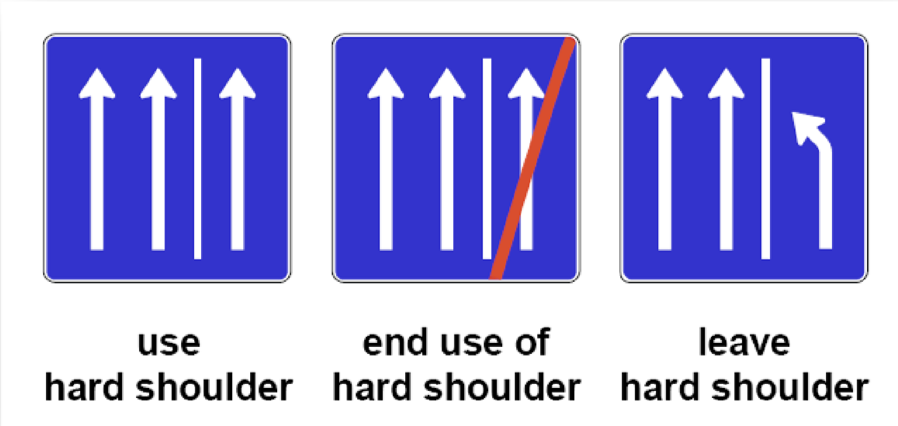

Figure 4. Forms of shoulder use sign (8).

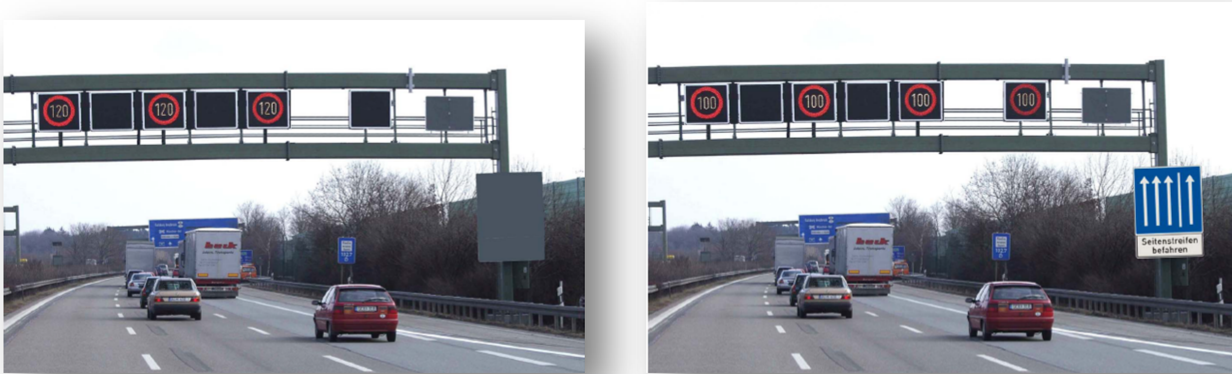

Figure 5. Hard shoulder for emergency only (left) and in use (right) (8).

The direction signing was designed to adapt to the enabling of shoulder use. This accommodation is commonly accomplished using rotating guide signs like those shown in Figure 6.

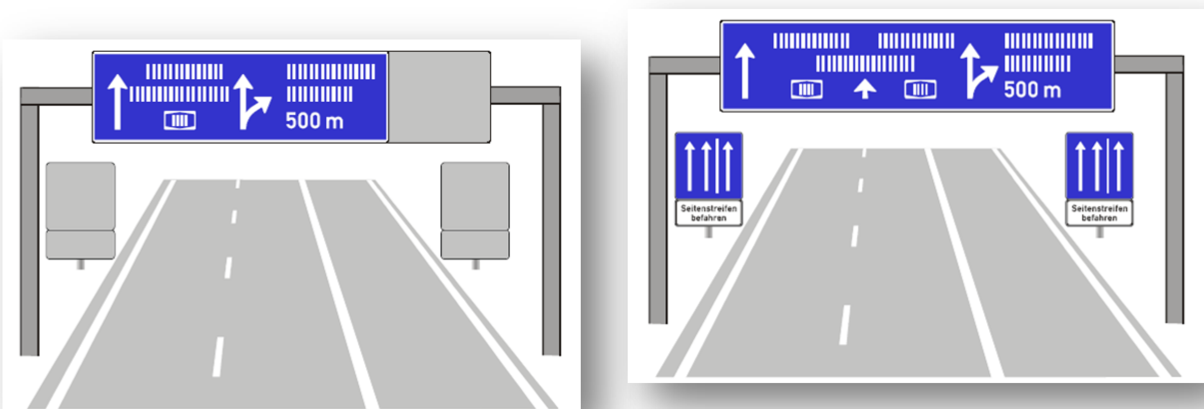

Figure 6. Direction signing without shoulder use (left) and with shoulder use (right) (8).

Safety evaluations for shoulder use were conducted by authorities, and no negative impact on safety was recorded. In fact, a reduction in congestion-related crashes was assumed. In terms of public opinion, a large majority of the traveling public is in favor of the measure, and positive feedback was received from users (9). Access to shoulders is not restricted to specific vehicles; trucks are allowed on the shoulders.[1]

According to a study in Hessen, when driving on the shoulder is allowed on a three lane motorway, the capacity is increased by 20 percent, allowing over 7,000 vph without breakdown. Conversely, without shoulder use, breakdown would occur at approximately 5,850 vph (9).

[1] Kuhn, B. *PCM International Scan Tour—Germany*. Frankfurt, Germany: Unpublished Personal Notes. June 2006.

An economic analysis on the A5 showed that shoulder use saves 3,200 vehicle hours in congestion per day, which is equivalent to a savings of €48,000 per day or €10 million per year. Those savings do not include any environmental benefits as a result of improved traffic flow. The amount invested in making shoulder use operational was €25.7 million: €13 million for the traffic control system and €12.7 million for strengthening the shoulder (9).

Shoulder Use in the Netherlands

Since 1994, the Netherlands has focused on making the best use of the existing transportation infrastructure in a safe and efficient way. Rijkswaterstaat—the Dutch Department of Transportation, Public Works, and Water Management—has implemented two types of shoulder uses. The first type of deployment uses the right shoulder, designated as HSR or rush hour lane. The second type of deployment uses a narrow left shoulder lane, called the plus lane. Standard shoulder widths are 1.25 m (4.10 ft) on the left shoulder and 3.0 m (9.85 ft) on the right shoulder. Since these widths are usually not chosen for shoulder use on either side, restriping is necessary most of the time. In 2006, 150 km (93.2 mi) of HSR/plus lanes were operational, and another 235 km (146 mi) were planned for the future.

The plus lane is typically a 2.7 m (9.25 ft) wide left lane striped just like a normal third lane (motorways in the Netherlands typically have two lanes). Its accessibility is determined by overhead lane control signs placed on regularly spaced gantries. When access to the plus lane is allowed, the speed limit is set to 70 km/h (44 mph) for all lanes (*10*). The safety issues caused by the narrower lane are reduced by this lower speed. This speed also allows a better quality of flow. However, because of the lost width on the lane, increased drivers attention is required. For that reason, transportation professionals found that the maximum appropriate length for this type of measure is 8 km (5.0 mi). The increase in road capacity due to this measure was evaluated at 42 percent for a two-lane motorway, with an improvement in safety as well. Other plus lane restrictions are that neither trucks nor vehicles more than 2.0 m (6.7 ft) wide are allowed to use it (*10*).

Right shoulder use in the Netherlands is similar to right shoulder use in Germany. The typical width for a usable shoulder is 3.5 m (12 ft), but it can be smaller in given situations. For safety purposes, shoulder use also requires a lower speed limit (8, *10*).

One key feature to enable a natural driving pattern on shoulders is to have variable route signs. The signs must adjust to the current width of the road in use and show arrows as if the shoulder was another general purpose lane. These signs can be either DMS or rotating guide signs (*10*).

Initially, HSR was only used in between junctions. This approach forced traffic to either merge into the two through lanes or exit at a junction. Current installations include acceleration and deceleration tapers, which allow continuous HSR use through a junction. Dynamic pavement markings are useful to signalize merging/exiting areas depending on the state of HSR. The use of HSR is deployed at the traffic management center (TMC) in coordination with the national headquarters. Models are used to evaluate the benefits and possible problems or shifting of bottlenecks downstream of the HSR section. Typically, once volumes reach 1,500 vphpl, an operator at the regional TMC will inspect the shoulder for debris or stalled vehicles using the network of cameras. If the shoulder is clear, the TMC operator will enable HSR. Some motorway sections have HSR active for up to 8 hours daily, but 24-hour operation is not recommended (8, *10*).

Initially, public reaction for shoulder use in the Netherlands was positive. However, stakeholders (e.g., fire brigade, police, emergency medical services, etc.) showed reluctance to the idea. Rijkswaterstaat found it necessary to communicate with stakeholders and to establish an incident management policy. Emergency refuge areas are placed along the shoulder every kilometer (*10*). In terms of safety, a significant improvement was observed on every section (*10*). The ministry of transport made €380 million available for the construction of 150 km (93.2 mi) of HSR/plus lanes in 2003 (*11*).

The "flexroad" (dynamic cross sections) is a concept based on dynamic pavement markings that could allow modeling the cross section to demand in real time. Figure 7 shows two states of a section of the A44. This is achieved by devices that are incrusted into the pavement. These can be turned on or off to materialize different sets of pavement markings (*12*).

Figure 7. Left, a "flexroad" with its two possible cross section on the A44. Right, a LED based pavement device used for dynamic lane marking (8).

Shoulder Use Experiences in the United States

In the United States, the primary use of shoulders has been as a safety refuge area. The limited shoulder use as a travel lane has been primarily reserved for special users of the roadway system, most often transit vehicles. Some shoulder use dates back to the 1970s, and many installations have been in operation for more than 10 years to address congestion on urban corridors (*13*). Agencies have seen bus use of shoulders as a low-cost and quick strategy to improve bus operations and reliability without having to acquire additional right-of-way and invest additional large sums of money into the infrastructure. The length of these deployments varies depending on location, ranging from a more than 290-mi comprehensive network in the Minneapolis-St. Paul metropolitan area to deployments less than 1 mi in length used to serve as a queue jump for transit in Delaware. The operational strategies often depend on the congestion on the general purpose lanes and often require speed restrictions of the transit vehicles using the shoulders.

Overall, experience using shoulders for interim use has been positive in the United States, and more agencies are considering the strategy to address growing congestion on their urban freeway networks (*14*). In fact, several states have deployed temporary shoulder use for all vehicles on congested corridors with success. Another application that is much more difficult to research and document is the number of locations where an existing shoulder has been narrowed or taken away to allow for widening with an extra permanent travel lane. This method is more commonly used in roadway work zones to maintain the existing number of travel lanes during construction. However, it has been applied in some permanent forms as well (*14*).

Studies performed at the Texas Transportation Institute (TTI) showed reducing the lane width in order to add an extra traffic lane had a positive impact on all travel time, capacity, safety, and quality of operations. The increase in absolute number of crashes that can be expected due to the narrower lanes is offset by the additional capacity (*15*). Comments suggested that it is not so much the level of hazard that is increased when lanes become narrower, but the driver's level of attention that needs to be higher.

Speed profiles on narrow lanes have been shown to be similar to those on regular lanes except in the case of level of service (LOS) F where the speed would be slightly lower (*16*). The same research study found that global accident rates could even be lower with narrow lanes if lane continuity and lane balance are respected. However, truck accident rates seem to be always higher on freeways with shoulder use and narrow lanes. It is recommended that narrow lanes be applied only to short sections for these reasons.

In 2008, TTI and Parsons Brinckerhoff created guidelines for New York State Department of Transportation (NYDOT) to help in decision making for managed lanes strategies. According to these guidelines, shoulder use is to be accompanied by speed harmonization and dynamic message signs over or next to the shoulder to indicate when the shoulder is in use. Once the shoulder has been checked to be clear of obstacles, an operator allows traffic to access the shoulder. The criteria to consider converting a regular shoulder to a useable shoulder are (*17*):

Essential criteria:

- LOS E/F for at least 2 hours in at least one peak period;
- Length of facility sufficient to alleviate a series of bottlenecks, at least 3 miles;
- Low volume of entering/exiting vehicles if crossing multiple interchanges;

- Minimum shoulder width of 10 ft., with ability to add emergency refuge areas; and
- Pavement strength to accommodate increased traffic load.

Desirable criteria:

- Active incident management;
- Existing ITS/ sensors;
- Ability to deploy speed harmonization concurrently; and
- Low turning movements (for arterials).

The left shoulder, or inside shoulder, can also be removed to add a lane and increase capacity. This was done in both Texas and California. Crash data for Dallas, Texas, showed no statistical difference between accident rates per million vehicle miles travelled (MVMT) on sections with and without inside shoulders (*18*). In Los Angeles, California, the number of crashes dropped remarkably and remained low over time when inside shoulders were removed to increase capacity (*19*). Research studies have shown the severity of accidents are not made worse by removing the inside shoulder. There are "either non significant changes or a significant reduction in overall accident rates." A scanning/feasibility study on active traffic management conducted for Washington State Department of Transportation (WSDOT) showed that shoulder use is an effective way to increase to capacity and reduce congestion in a small amount of time. The cost of preparing a freeway for shoulder use was estimated at $2.7 million per mile (*20*). Table 1 provides a summary of the advantages and disadvantages of shoulder use alternatives included in the WSDOT feasibility study.

Table 1. Advantages and disadvantages of shoulder use design alternatives (*20*).

Design Alternatives	Advantages	Disadvantages
Use of Left Shoulder	• Left Shoulder not used as much for emergency stop/or emergency enforcement • Least expensive if width is available • Trucks often restricted from left lane	• Usually requires restriping • Sight distance problems with some median treatments
Use of Right Shoulder	• Often the easiest to implement	• Right Shoulder is preferred area for emergency stops and enforcement • Sight distance changes at merge and diverge areas of ramps
Use of Both Shoulders	• Not recommended • Use ONLY is extreme cases	• Requires restriping • Safety concerns (no refuge) • Enforcement is difficult • Incident response longer • Maintenance more difficult and more expensive

In the U.S., temporary shoulder use varies. On Massachusetts State Route 3 and I-93 and I-95 in the Boston area, all vehicles are permitted on shoulders in the peak periods only. Similarly, in Virginia on I-66, the shoulder carries general purpose traffic from 5:30 a.m.–11:00 a.m. (eastbound) and 2:00 p.m.–8:00 p.m. (westbound); however, during this time, the interior general purpose lane is open to high occupancy vehicle (HOV) traffic only. I-66 uses extensive traffic signals and signage in order to communicate the active times of service. In the Seattle area, the right shoulder on the US 2 trestle near Everett is opened to all traffic in the eastbound direction during the afternoon peak period. A similar operation is provided on H1 in Honolulu in the morning peak on the right shoulder. A unique combination of strategies is operational on I-35W in Minneapolis where a segment has the left shoulder open during the peak periods. Known as priced dynamic shoulder lanes (PDSL), transit and carpools use the shoulder for free and MnPASS customers can use the shoulder for a fee (*14*).

A Special Treatment of Shoulders: Transit-Only Access

Another type of shoulder use involving transit-only use of the shoulder has proven successful in several North American cities in variable forms. Several states, including Florida, California, Georgia, and Ohio, are moving to enable this type of treatment. Among all bus bypass shoulder (BBS) projects, very few have been abandoned after implementation. Projects that were abandoned were usually replaced by dedicated bus lanes indicating that these cities wanted to go further in improving transit performance.

The motivation behind this measure is to encourage transit use and fully utilize the capacity of the transportation system (*21*). The treatment is very popular with bus riders for apparent reasons. It has several advantages: reduction of travel times variability due to congestion which helps schedule reliability, competitive travel time compared to cars, low deployment cost, easy to implement, does not require extra right of way, and the buses do not visually obstruct other vehicles' line of sight (*22*).

In Minneapolis, BBS has been proven to be both safe and effective. In fact, improvements were such that schedules had to be rewritten and unneeded buses were taken off route schedules due to increased efficiency (*21*). Perceived travel time savings range from 5 to 15 minutes for each passenger with an average of 7 minutes. The main factors impacting the ease of implementation are the width of the shoulder and the shoulder pavement thickness (*13*).

For an arterial or freeway to qualify for BBS, MnDOT established a list of criteria. Most importantly the facility must experience "predictable congestion delays," in other words, the speed must drop below 35 mph during the peak period or approaches to intersection must suffer continuous queues. Other criteria include congestion delays that occur at least once a week, at least six transit buses will use the shoulder in a week, the delay savings must be greater than 8 minutes per mile per week and the shoulder has to be at least 10 ft wide (*21*).

MnDOT issued guidelines to transit bus drivers to ensure the safety of passengers and all other users of the facility. To avoid speed differentials with the main traffic, shoulder use is only allowed when the speed drops below 35 mph. Buses using the shoulder are not allowed to drive more than 15 mph faster than main traffic, and the maximum speed on the shoulder is 35 mph (*21*). Figure 8 illustrates the typical signing layouts used in Minnesota.

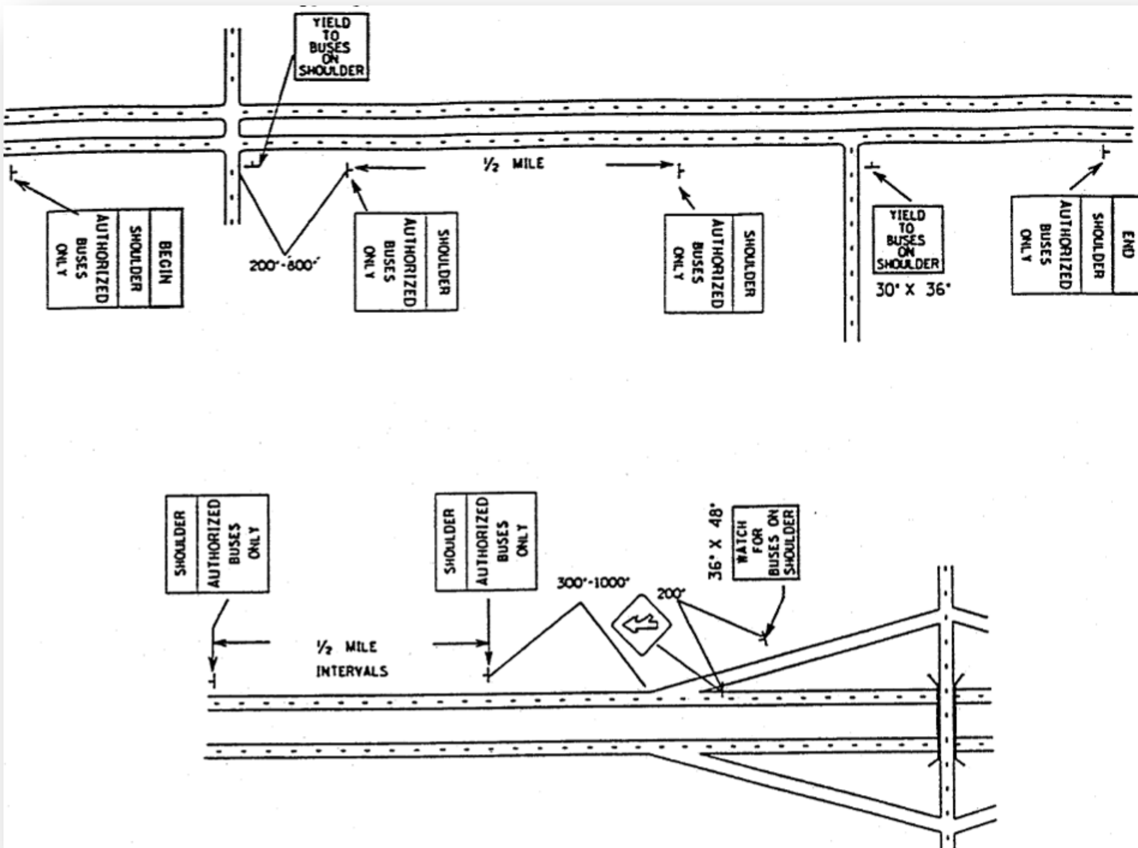

Figure 8. Typical signage for BBS as described by MnDOT (*21*).

Other screening criteria for BBS treatments were also provided to the NYSDOT, which were separated into essential and desirable categories as noted below (*17*):

Essential criteria:

- LOS D or worse for 2+ hours for at least one peak period, to have room for improvement bus travel time reliability;
- At least 10 ft shoulder width (or parking lane space on arterials) available;
- Sufficient pavement strength to sustain bus load; and
- Minimum volumes: arterials 25 buses/hr, freeway 50 buses/hr.

Desirable criteria:

- Travel time variability higher than 1 minute per 2 miles;
- Acceptable changes for on-street operation;
- Few conflict points at junctions (less important); and
- Portion shared with multiple bus routes (less important).

In Virginia, the shoulder has a double use. During specific times of the day, the shoulders are allowed to be used by general traffic, and at other times only HOV2+ vehicles are allowed to use the shoulders. The Virginia Department of Transportation (VDOT) assures this type of use of the shoulder has no significant impact on the number of crashes (*23*).

Speed Harmonization

The concept of speed harmonization, also called variable speed limits or dynamic speed limits, is already in place in many countries and several states in the United States. Agencies choose speed harmonization to solve very different problems. The two most cited purposes for deploying speed harmonization are for weather related conditions and congestion management. Depending on the goals of the agency, the speed can either be mandatory or advisory.

Weather Related Speed Harmonization

Weather related speed harmonization is often used on roads where fog, ice, rain, or other factors often impact safety. Several northern European countries have witnessed disastrous pile-ups due to ice or heavy fog. Funding was made available in Finland for real-time driver information and speed control (*24*). In both Finland and Sweden, local weather stations collect weather conditions and pavement-embedded sensors measure pavement characteristics, allowing a system to post an accurate safe speed for all users. That speed is then displayed on DMS with a message or pictograph of the reason for the new speed limit. In Finland, the Road Weather Information System (RWIS) uses the data from all weather stations to inform travelers of weather and road surface conditions in real-time and with a short-term forecast. This practice has proven very useful to organize winter maintenance teams. Public acceptance of this type of speed harmonization is good; no marketing was needed because drivers easily understand the function of the system (*25*).

Sydney, Australia, implemented a fog warning system, which includes advisory speeds. During fog, the advisory speed limit is continuously adjusted to the speed of the preceding vehicle within the speed limit (*26*).

In Denmark, studies found that a DMS indication of slippery road, fog, and other hazardous road conditions reduced the traffic mean speed by 1 to 2 km/h. When the speed harmonization sign showed a speed limit of 80 km/h instead of 100 km/h, the mean speed was reduced by 3.4 km/h. In adverse road conditions, such as black ice, the speed limit was lowered from 120 km/h to 100 km/h mean speed dropped by 5.1 km/h. The speed harmonization signs also reduced speed variance (*27*).

The Netherlands also deploy speed harmonization for weather conditions. Visibility sensors are used to measure the level of fog and when visibility drops to 140 m or 70 m, the speed limit is dropped to 80 km/h or 60 km/h, respectively. After implementation of the speed harmonization during fog conditions, drivers reduced their speed by 8–10 km/h (*28*).

Congestion Related Speed Harmonization

Congestion related speed harmonization is used, as the name suggests, during periods with high traffic volumes or congested situations. The Netherlands was one of the first countries to utilize this strategy. It is believed that speed harmonization can be used to create a better uniformity in speeds and a sustainable traffic flow. The speed limit was set to a one-minute average of speeds across lanes. When deployed, this method yielded a high compliance rate, and the severity of shockwaves was significantly reduced (*28*). Figure 9 shows a typical speed harmonization sign in the Netherlands.

Figure 9. Speed harmonization in the Netherlands (*12*).

The motto for many agencies can be summarized as "drive slower, arrive faster." The underlying idea of the motto is that a slower, more consistent, flow is less likely to break down into congested flow, therefore improving travel times. Volumes and speeds are mainly measured through inductive loop detectors. The speed limit is changed automatically by using the information from the loops in a computer algorithm. By gradually reducing the speed as volumes are predicted to increase, this strategy allows a slight increase in capacity. In the case of the Netherlands, the increase was 5 percent. This strategy also avoids an abrupt transition into congested flow (*25*).

The M25 motorway was the first to introduce speed harmonization in Britain in 1995. Currently, 60 percent of motorists believe the plan is beneficial, and results show 6 percent fewer stop and go situations. This reduction results in a decrease in emissions by 2 to 8 percent, a noise reduction around 0.7 decibels, 20 percent fewer property damage only crashes, and 10 percent fewer injury crashes (*29, 30*). Implementation has also resulted in an improvement in travel time reliability, a smoother flow, a better lane balance, and a calmer driving experience. Setting up gantries regularly to support the speed displays and enforcement cameras have increased speed compliance even when no speed restriction is applied, resulting in increased travel times. A benefit/cost analysis on that portion of controlled highway was negative, but the implications of the operation were broader than the study accounted for and further analysis is needed (*30*).

In all of the European countries surveyed, the signing for speed harmonization and most other active traffic management tools like queue warning and shoulder use are placed on overhead gantries. These installations have the advantage of providing unobstructed visibility for every lane (*31*). In the Netherlands, the speed on the sign can be accompanied by flashers when there is a speed drop and red circles meaning the speed limit is enforced; however all posted speeds are regulatory (*28*).

Facilities in Germany with speed harmonization had travel times reduced by 5 to 15 percent, the number of crashes decreased by 30 percent, and a 5 percent increase in capacity (1, *26*). In Denmark, the implementation of speed harmonization resulted in speeds decreasing by less than 5 km/h and reduced speed variance. A survey showed that 46 percent of Danish travelers felt safer after the implementation (*32*).

A feasibility study in Washington predicted reductions in injury collisions of 30 percent and all other collisions by 16 percent. The study concluded that the benefits from reduced travel times and delays would exceed the cost of the program in anywhere from 4.5 years to as little as one year (*20*). A conceptual rendering of a WSDOT installation is shown in Figure 10.

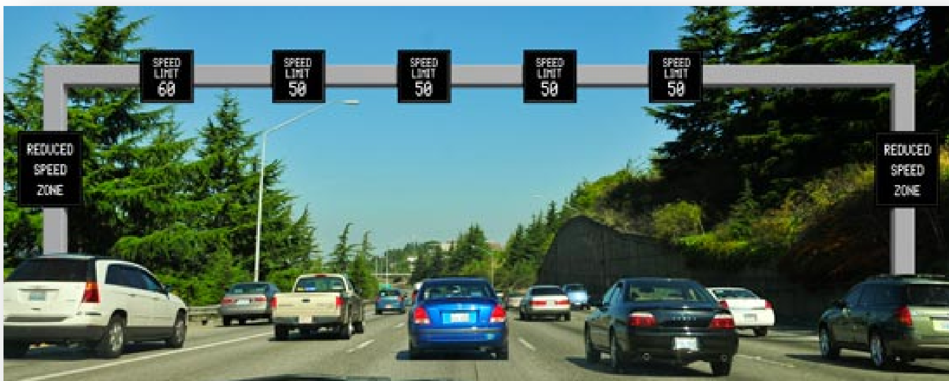

Figure 10. Gantry concept for WSDOT, with an HOV lane on the left side (*33*).

The criteria for speed harmonization suggested in a study by the TTI and Parsons Brinkerhoff to the NYDOT were divided into to the categories of essential and desirable. The criteria recommended were:

Essential criteria:

- LOS E or F for minimum 3 hours for at least one peak period and at least 5 hours per day;
- Right of way for overhead gantries and DMS;
- At least one location every 2 miles where queues form and warning is warranted; and
- At least five incidents related to queuing, merging, and/or diverging per week.

Desirable criteria:

- Willingness to automate the deployment of strategy; and
- Existing ITS and connections to TMC.

In the United States, some locations that have implemented speed harmonization use a ground mounted sign instead of a more expensive gantry. This approach has raised some concerns in the population as the sign could be obstructed and that they could be fined for speeding unknowingly (*34*).

Speed harmonization is commonly used with automated queue detection/warning and lane control signs. In the Netherlands and England, this function is part of incident detection and management programs, respectively, named MTM (motorway traffic management) and MIDAS (Motorway Incident Detection and Automatic Signaling). In Sweden this type of system helped reduce serious accidents by 35 percent and secondary accidents by percent, for an overall reduction of 23 percent. In Germany, accidents were reduced by 20 percent at the same time that they increased by 10 percent on a similar autobahn without speed harmonization (*35*).

Speed harmonization is also regularly used in combination with shoulder use. In all surveyed countries that implemented shoulder use, the use of the shoulder was only allowed at a speed below the standard speed limit. In Germany for instance, the speed limit is changed from 120 km/h (or other posted limit) to 100 km/h (8).

Compliance and Enforcement

The success of speed harmonization is closely linked to the extent to which drivers comply with the signing. The experience in four countries (Netherlands, Germany, Sweden, and Australia) led to the identification of basic guidelines for a speed harmonization strategy. Communication has to be of paramount importance and should aim at the jurisdiction, the police, the engineers, and especially the public. The strategy also has to be success-oriented with a fair and reasonable plan for the majority of users. For instance, placing a 20 mph limit on a freeway to force a speed reduction is bound to fail and will reduce public confidence in traffic management strategies (*26*).

Travelers are usually not familiar with these new signs on the road and usually have plenty of unanswered questions regarding the signs. Thus, it is important that agencies communicate with the public and inform them of new measures and regulations as they are put in place. In many European countries and Australia, a high emphasis on outreach and education helped bring better compliance.

Speed harmonization needs to be implemented in response to an actual situation. If users do not believe the system is legitimate, compliance rates will be low. Therefore, if the reason for the new speed limit is not apparent, it should be explained through appropriate signing. A report on speed harmonization on the M25 in England explains that in the beginning of the project the speeds displayed had no connection to a congested situation or incident; therefore the speed limits were largely ignored by the driving public (*30*).

When speed harmonization is used with hard shoulder running, the compliance rates on M42 in England show that shoulder users tend to comply better with the speed limits (5). Compliance rates were seen as follows:

- On the main lanes:
    - 94 percent or better for speed limits of 70, 60, and 50 mph; and
    - 87 percent or better for speed limits of 40 mph.
- On the hard shoulder:
    - 98 percent for 50 mph speed limit; and
    - 93 percent for 40 mph speed limit.

In many situations automated enforcement is used, however police vehicles can also monitor speeds manually. Automated enforcement is used as a prevention method rather than a repressive or profitable measure. It is also an economic means of enforcement in terms of manpower and efficiency (*26*).

When enforcement is chosen to improve compliance, it is necessary to implement the enforcement using a phased approach. This approach includes education and communication to explain the importance of speed compliance. Enforcement may also be chosen to use average speed control between two distant gantries rather than spot speed control that is predictable even if the cameras are randomly set. In that case, speeders cannot simply slow down to pass the cameras, and will be caught if their average speed is higher than the limit over the controlled stretch, which can be as long as 17 km (5).

Imposing variable speed limits on the driving population may lead to significantly lower compliance. Using automated speed enforcement cameras can be an effective solution to this problem. In France, an aggressive country wide speed enforcement policy managed to reduce the number of speeders from 7 percent to fewer than 3 percent of all drivers in camera enforced locations. Political support is strong: 86 percent of the population admits to reducing their speed because of the cameras, and 77 percent believes that the enforcement improves road safety (*36*). Figure 11 shows the typical signing and equipment used for speed enforcement in France.

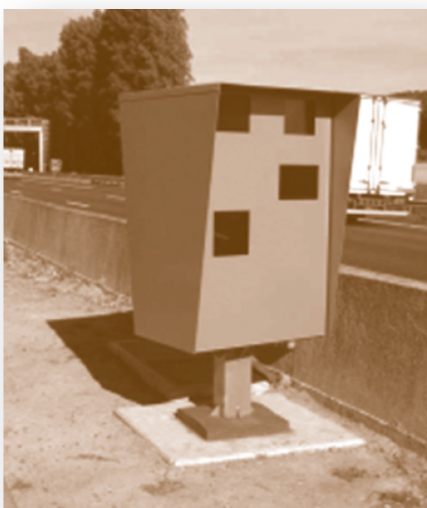

Figure 11. A fixed enforcement camera and warning sign, France (*36*).

Other Approaches to Improve Speed Compliance

Speed can also be reduced through the driver perception of risk. Narrower lanes and noise inducing tactile strips (rumble strips) are approaches that result in the driver perception of risk. By applying these in the Netherlands, a speed reduction between 5 and 10 km/h was observed and the safety on the road was not compromised. There was a 35 percent reduction in crashes on trial roads while control road crashes increased by 17 percent. These measures prove especially efficient on roads were the perception of risk is too low for users to decrease their speed (*26*).

It is possible to inform drivers of their speed without taking action to force self-moderation. Using a DMS sign showing every driver speed and whether they're driving too fast or too slow has been proven to be an efficient method that does not involve the presence of an authority. In Germany, this technique was used to encourage people to drive between 60 and 80 km/h and the number of speeders decreased from 38 to 11 percent with an average speed reduction of 3 to 8 km/h, the number of vehicles going under 60km/h slightly increased (*25*). In France, on the A7, an experiment was conducted whereby non-complying drivers have their plate number displayed on overhead DMS with a notice of the violation, but no fines are issued. Their speed is determined on a stretch of 10 km delineated by two gantries that are equipped with automated vehicle identification (AVI). The results are promising with 80 percent compliance at 110 km/h but a lower 50 percent at 90 km/h.

Queue Warning

The basic principle of queue warning is to inform travelers of the presence of upstream queues, based on dynamic traffic detection and using warning signs and flashing lights. This strategy allows the traveler to anticipate a situation of emergency braking and limit the extent of speed differentials, erratic behavior, and queuing-related collisions. Figure 12 is an example of a queue warning installation in Germany. The pictogram warning can be turned on manually by a TMC operator or automatically when it is integrated into an incident management program such as MIDAS (England). The DMS signs on England's network are primarily used by the national traffic control center, but MIDAS can override the messages if deemed necessary (*29*).

Figure 12. Queue warning in Germany.

In the Netherlands, on heavily traveled routes with an average daily traffic (ADT) over 60,000 vehicles per day, "about 50 percent of the accidents are caused by severe disruptions in the traffic flow, caused themselves by accidents or queues" (*12*). The chance of having a queuing-related accident becomes virtually absent 20 minutes after deploying the warning. This statistic indicates the benefits of detecting these disruptions as quickly as possible.

Results on the A8 Autobahn between Ulm and Stuttgart in Germany show that queue warning improves the quality of traffic flow, reduces speeds with closer headways, encourages more uniform driving speeds , and slightly increases capacity. Since drivers anticipate the risk of queues, accidents are less severe and less frequent. It was also noted that users are interested in knowing the location of the queue and what route they should take to avoid it (1).

When queue warning is included in a larger traffic management project that has lane control signals and variable speed limits with DMS, it is possible to reduce the speed incrementally between gantries and evacuate traffic from one lane to provide access and shelter for emergency vehicles. This procedure, called automatic incident detection (AID) in the Netherlands, is illustrated in Figure 13. In Sweden, this type of system helped to reduce accidents by 23 percent overall, specifically serious accidents decreased by 35 percent, and secondary accidents decreased by 46 percent. In Germany, accidents were reduced by 20 percent on an autobahn with queue warning while they increased by 10 percent on a similar autobahn without queue warning (*35*).

Work zones also take advantage of queue warnings. Many agencies use mobile DMS to warn approaching traffic of queues. The results are very positive, an example being, in Belgium where 60 percent of rear-end crashes were avoided (*31*).   On some roads, like on both the inner and outer ring roads in Paris, France, congestion occurs so regularly that users are much more interested in knowing the expected travel time to their exit than the presence of downstream queue (*37*).

A study in Washington found that queue warning could reduce congestion related collisions by 15 to 20 percent and that the benefits were estimated to outweigh the cost within 1 to 3 years (*20*). The criteria assessment for queue warning made by the Texas Transportation Institute and Parsons Brinkerhoff for the NYDOT, shows the following (*17*):

- Essential criteria:
    - LOS E/F for at least 2 hours per peak period;
    - Presence of queues in predictable locations;
    - Sight distance restricted by vertical grades, horizontal curves, or inadequate illumination;
    - Right of way for overhead gantries and DMS; and
    - At least five incidents related to queuing merging and diverging per week.
- Desirable criteria:
    - Large mix of high profile vehicles or inability to control speeds;
    - Presence of speed harmonization on the facility;
    - Willingness to automate the deployment of strategy;
    - Existing and sufficient ITS; and
    - Connection to a TMC that serves as the focal point for the system.

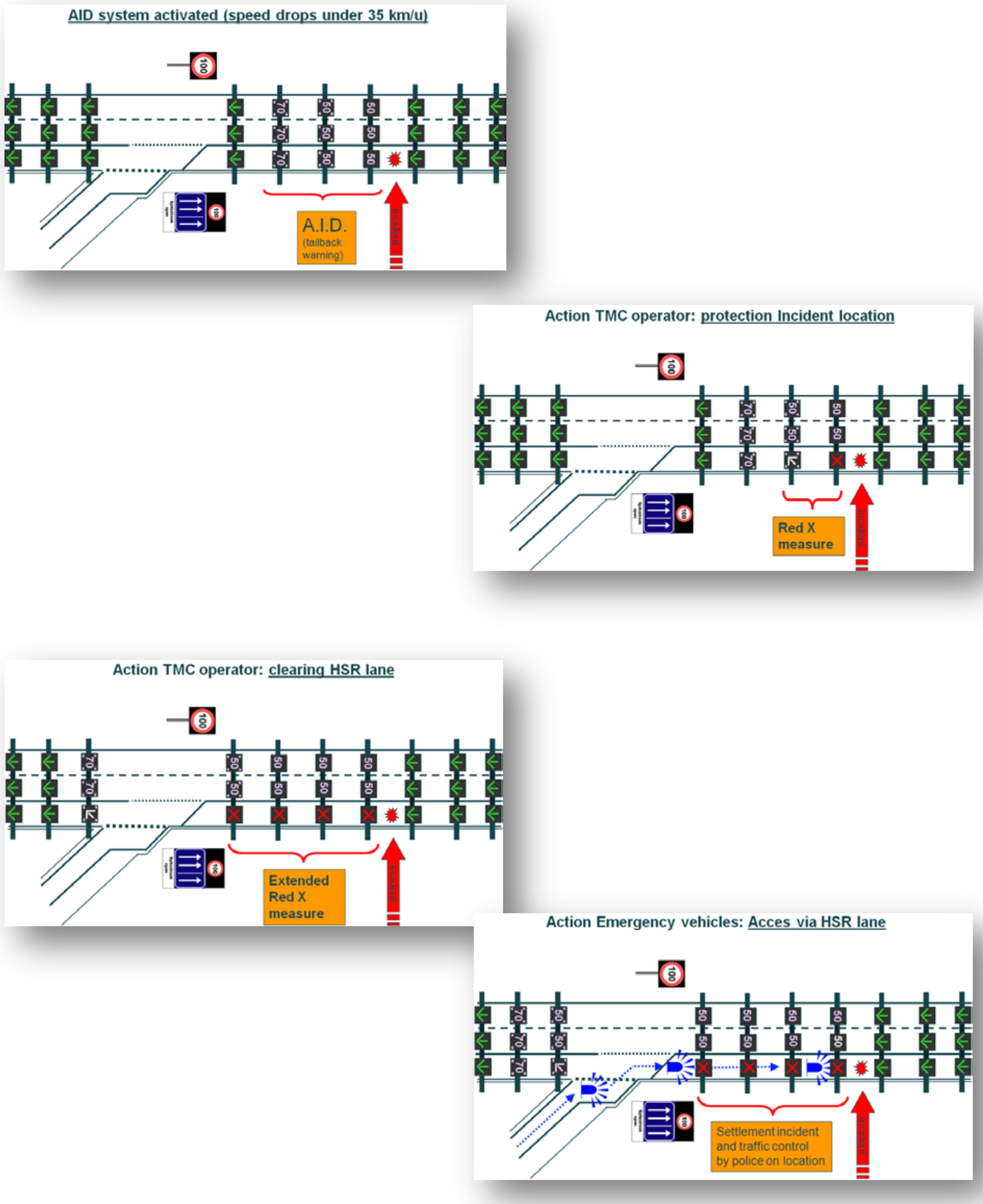

Figure 13. Four step incident response protocol with shoulder use in the Netherlands (*10*).

Dynamic Merge Control

Dynamic merge control, also termed junction control, is used when the sum of both freeway general purpose lanes and merging lanes at an interchange is higher than the number of downstream general purpose lanes. A combination of ramp metering and lane control at ramps, dynamic merge control is used to dynamically meter or close specific lanes upstream of the interchange to manage access based on traffic demand (1). A typical U.S. application of this condition would be a lane drop for one of the outside lanes or a merging of two inside lanes, both of which are static solutions. Figure 14 illustrates the German approach in which lane control signals are used to close the rightmost general purpose lane upstream of the on-ramp to allow two ramp lanes to merge onto the motorway. The intent is to provide dynamic priority access to the higher traffic stream. Dynamic merge control can be a permanent application, or it can be used temporarily until a downstream roadway is widened (*35*). It is a practical approach to handling varying demand on the main lanes and the merging lanes to effectively utilize existing capacity.

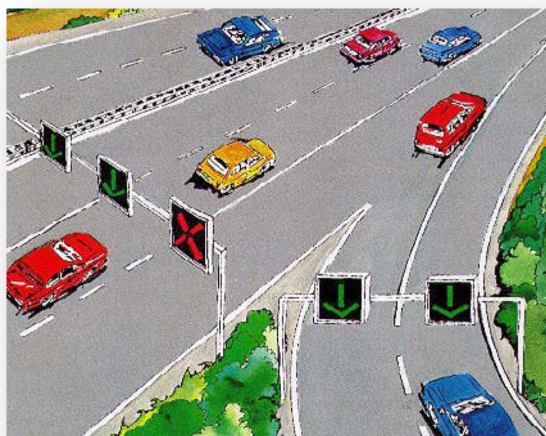

Figure 14. Dynamic merge control schematic (*38*).

In the Netherlands, a pilot test of dynamic merge control on the A1 showed promising results (*28*). In the state of Washington, this measure—if implemented—is expected to reduce collisions by 20 to 25 percent; the benefits of avoided collisions would most likely outweigh the primary cost in about 6 to 8 years (*20*). The criteria assessment for dynamic merge control made by the TTI and Parsons Brinkerhoff for NYDOT provided essential and desirable criteria, which included the following (*17*):

- Essential criteria:
  - High volume of entering traffic, at least 900 vph; and
  - Available capacity in the upstream general purpose lanes to be borrowed with no worse than LOS E after implementation.
- Desirable criteria:
  - Active incident management; and
  - Existing ITS/sensors.

Dynamic Rerouting and Traveler Information

When the main road is congested, rerouting traffic on a parallel road to relieve further congestion can be an efficient strategy. Providing rerouting and traveler information in a dynamic manner is a critical component of a successful ATM system. The intent is to provide users with viable route alternatives, and the approach can be especially beneficial in helping reduce the impact of noncurrent congestion (1). When considering dynamic rerouting and traveler information, there are two signing strategies that can be applied: substitution and addition. In the substitution strategy, rotating panels on guide signs turn and indicate the suggested secondary route. The problem encountered with this method is that the first route is no longer displayed, and some mid-trip destinations may be missed. In the addition strategy, orange arrows show the recommended diversion route while keeping the original signing. In both cases, full matrix DMS can be used to display any of those strategies (*39*).

One scenario proposed for WSDOT, pictured in Figure 15, shows two separate approaches to sign for dynamic rerouting. A study on dynamic rerouting and traveler information in Copenhagen, Denmark, suggested that more travelers followed the alternative route (up to 12 percent of the time) as the displayed travel time between the original and alternate route increased. The relatively low portion of route changers may be due to erratic displays on DMS at the time of deployment. Surveys conducted showed that 80 percent of the driving public was in favor of this system (*32*).

Figure 15. Two types of substitute rerouting by WSDOT (*20*).

In the Netherlands, rerouting information is displayed using through full matrix DMS that provide useful information for drivers to make the appropriate decision based on their needs. These signs are usually set at entrances of cities. Evidence indicates that the use of these signs has helped reduce congestion. For instance, after implementation on the Amsterdam ring road, congestion dropped by 25 to 33 percent. Drivers give more credit to the provision of accurate information (62 percent) to DMS information than to radio (52 percent) (*12*). In normal conditions, 8 to 10 percent of drivers are reacting to the information. This trend can have a major effect on roadway operations and recurrent congestion (*28*). Figure 16 shows a DMS showing two routes to Schiphol and a notice that both routes are congestion free. For important interchanges, like the one depicted in Figure 17, the amount of information to deliver for every possible route is too important for textual signing; therefore, a graphical approach is chosen.

Figure 16. Route information in the Netherlands (*12*).

Figure 17. Graphical route information in the Netherlands (*12*).

In England, an expert system in the TMC computes the remaining capacity on a facility and the anticipated demand for the duration of an incident. If the anticipated delay exceeds a set threshold, the demand on alternate routes and the presence of road works, weather problems, or special events is evaluated before communicating the alternate route to the traffic (*29*).

Some general criteria assessment for dynamic rerouting provided to NYDOT includes the following (*17*):

- Essential criteria:
  - Level of service E/F for 2 or more hours in at least one peak period;
  - At least 3 incidents per week resulting in severe congestion;
  - The presence of a viable parallel and comparable corridor to accept rerouted traffic no farther than 2 mi from the primary corridor;
  - Available capacity on the parallel facility; and
  - Available right of way for overhead gantries to provide routing information.
- Desirable criteria:
  - Existing ITS/sensors; and
  - Concurrent implementation of speed harmonization.

Dynamic Truck Restrictions

Restricting trucks to the right lane has several benefits. The treatment can increase capacity by up to 3 percent, the speed of the left lane can be higher, and safety is improved since no trucks are changing lanes. Eventually, the flow becomes more stable and homogeneous (*40*). However, in Europe, trucks do not have the same speed limit as cars, and in most countries, the difference between the two limits is 20 to 30 km/h. Trucks are also instructed to drive on the rightmost lane except for passing, which when combined with the mandatory speed differential is often a restriction to the right lane itself (*41*). Although most drivers agree with the measure, the trucking industry is not very supportive.

In the Netherlands, until the dynamic aspect was introduced recently as a test, the restriction took place at fixed times of the day mainly during peak hours. The dynamic restriction is activated when necessary and is displayed on overhead gantries. The approval rates for the dynamic variation are better among truck drivers and fewer violations were reported (*12*). Figure 18 shows an example of dynamic truck restriction in the Netherlands. Some sections where speed harmonization is present also have dynamic truck restrictions that are implemented at the same as the speed harmonization. The combination of these two strategies has showed to reduce accidents enough to pay for itself in three years (*39*).

Figure 18. Dynamic truck restriction in the Netherlands (*41*).

Depending on the location, truck restrictions might not be a solution for a congestion problem. In England, a section of the M5 that regularly experienced congestion with up to 19 miles of queue was used as a pilot scheme for truck restrictions. The restriction applied to towing vehicles, buses, and heavy goods vehicles (HGV). Although the right lane usage by trucks increased from 84 to 91 percent, the levels of congestion were not significantly affected as the congestion was mainly due to car traffic (*42*).

Chapter 3: Best Practices and Guidelines

After reviewing the extensive literature related to ATM and assessing deployments from across the United States and Europe, the following high-level general guidelines for the deployment of ATM were developed. Included in these guidelines are a brief description of each operational strategy, data needs, essential and preferable elements, key factors, and potential impacts and benefits. The intent is for transportation professionals to use this document to identify the most appropriate ATM strategy for their jurisdiction. Those ATM operational strategies included in the guidelines are shoulder use, speed harmonization, queue warning, dynamic merge control, dynamic rerouting, and dynamic truck restrictions.

Guidelines for Shoulder Use

Shoulder use, also known as HSR, is a dynamic measure designed to adapt roadway capacity to high traffic flow on a temporary basis. By allowing vehicles on the left or right shoulder under reduced speed limits, it is possible to serve a higher number of vehicles and avoid congestion, totally or partially, during peak hours. The decision to implement shoulder use on a segment is taken by the operator in the traffic management center, although the need to open the shoulder is based on volume considerations. Two approaches to temporary shoulder use are implements allowing all vehicles or only transit vehicles to use the shoulder.

- *Shoulder use for all vehicles* allows all vehicles on the roadway to utilize the designated shoulder when open. Traffic control devices over or adjacent to the shoulder instruct drivers when driving on the shoulder is permitted.
- *Transit-only shoulder use*, also known as a bus bypass shoulder or bus on shoulder (BOS), allows only transit vehicles to utilize the designated shoulder under specific conditions and driving regulations. This measure allows more reliable transit schedules during congestion and does not required extensive changes on the road. The bus drivers are instructed to use the shoulder under specific circumstances to ensure the safety of the operation and all the freeway users. They are typically allowed on the shoulder when the speed drops below 35 mph. The measure can also be applied to parking lanes on arterials.

Data Needs

At a minimum, the following data needs are necessary for successful implementation of temporary shoulder use:

- Traffic volumes;
- Travel speeds;
- Incident presence and location; and
- Shoulder availability.

Essential and Preferable Elements

General criteria for shoulder use for all vehicles include the following:

- Essential elements:
    - LOS E or F for at least 2 hours per day;
    - Facility segment under consideration at 3 miles in length;
    - No expected bottleneck downstream of the shoulder use segment;
    - Low volumes entering and exiting the facility especially if going through interchanges;
    - Minimum shoulder width of 10 ft;
    - Available right of way for emergency refuge areas and acceleration/deceleration tapers; and
    - Sufficient pavement strength on the shoulder to bear the traffic.
- Preferable elements:
    - Active incident management;
    - Connection to a TMC that serves as the focal point for the system;
    - Existing sensors and ITS; and

- Presence of speed harmonization on the facility.

General criteria for shoulder use by transit vehicles only include the following:

- Essential elements:
  - Predictable congestion delays, LOS D for 2 hours per day;
  - Minimum 10 ft shoulder width available;
  - Sufficient pavement strength to sustain bus load; and
  - Minimum service of 50 buses/hour (freeway) or 25 buses/hour (arterial).
- Preferable elements:
  - Travel time variability higher than 1 minute per 2 miles;
  - Few conflict points at interchanges;
  - Portion shared with multiple bus routes; and
  - Acceptable changes for on street operation (arterial).

Key Factors

The following are key factors to consider that can help facilitate successful deployment:

- Temporary shoulder use is typically implemented in conjunction with speed harmonization.
- When implemented with speed harmonization, speed limit signs and lane control signals need to be visible to all vehicles; therefore, the signs are to be placed on gantries over every lane of traffic. During normal operation, i.e., when the use of the shoulder is prohibited, all the signs—including the sign over the shoulder—are blank.
- Either the left or right shoulder can be used for the application, depending on the facility conditions. It is not recommended to apply shoulder use on both left and right shoulders of a facility at the same time.
- To ensure the safety on the shoulder, video cameras should be placed regularly to allow operators to check for obstacles before opening the shoulder to traffic and monitor operations while shoulder use is permitted. To avoid having stranded vehicles on a used shoulder, emergency refuge areas should be located at regular intervals along the shoulder with proper signing.
- Overhead guide signs should adapt to the current used width of the roadway. In other words, when the shoulder is open to traffic, guide signs should provide information to the shoulder lane as if it was a permanent travel lane. This can be accomplished with DMS.
- When acceleration and deceleration tapers are needed, additional tapers are placed on the right side of the shoulder since the original tapers are usually on the shoulder. The additional tapers are meant to be used only while traffic circulates on the shoulder.

Potential Benefits and Impacts

The following are potential benefits and impacts of speed harmonization, depending on local conditions and deployment approach:

- Increased throughput;
- Increased capacity;
- Increased trip reliability; and

- Delay onset of freeway breakdown.

Guidelines for Speed Harmonization

Speed harmonization, also called variable speed limits or dynamic speed limits, is an operational strategy where agencies use an expert system to monitor data coming from field-deployed sensors on a roadway and proactively and automatically adjust speed limits when congestion thresholds are exceeded and congestion and queue formation are imminent. The intent of the strategy is to adapt the speed limit to obtain a consistent and homogenous traffic flow and delay the onset of breakdown. The measure is used mainly in Germany, the Netherlands, and Great Britain. Two common purposes for deploying speed harmonization are for weather-related conditions and congestion management:

- *Weather Related Speed Harmonization* is often used on roads where fog, ice, rain, or other factors often impact safety. When weather conditions deteriorate to the point that hazardous conditions are impending, the operating agency reduces the speed limit to one that helps minimize the likelihood of incidents.
- *Congestion Related Speed Harmonization* is used during periods with high traffic volumes or congested situations. When volumes and/or speed exceed a predetermined threshold, the operational strategy is deployed. The intent is to foster better uniformity in speeds and a sustainable traffic flow.

In both cases, the decrease of the speed limit is intended to alert drivers of changing conditions downstream. Ideally, these changes are automated and do not require intervention from any operator. The speed limit changes in increments of 5 or 10 mph to progressively decelerate the flow of traffic. Depending on the goals of the agency, the speed can either be mandatory or advisory.

Data Needs

At a minimum, the following data are necessary for successful implementation of speed harmonization:

- Weather conditions;
- Pavement conditions related to weather;
- Traffic volumes;
- Travel speeds; and
- Incident presence and location.

Essential and Preferable Elements

General criteria for speed harmonization include the following:

- Essential elements:
    - LOS E or F for 3 hours during the peak hour and 5 hours per day;
    - Right of way available for overhead gantries and DMS at regular intervals;
    - At least one location where queues regularly form and warning is warranted; and
    - At least five incidents related to queuing, merging/diverging per week.

- Preferable elements:
  - Willingness to automate the deployment of the strategy; and
  - Existing ITS and connections to the TMC.

Key Factors

The following are key factors to consider that can help facilitate successful deployment:

- The success of speed harmonization is closely linked to the extent to which drivers comply with the signing, so it is important that agencies communicate with the public and inform them of new measures and regulations as they are put in place.
- Speed harmonization needs to be implemented in response to an actual situation. If users do not believe the system is legitimate, compliance rates will be low. Therefore, if the reason for the new speed limit is not apparent, it should be explained through appropriate signing.
- Speed limit signs have to be visible to all vehicles; therefore, the signs are to be placed on gantries over every lane of traffic. DMS should be placed regularly to either give explanation for the lower speed limits or warn about extraordinary events.

Potential Benefits and Impacts

The following are potential benefit and impacts of speed harmonization, depending on local conditions and deployment approach:

- Increased throughput;
- Decrease in primary incidents;
- Decrease in incident severity;
- More uniform speeds;
- Decreased headways;
- More uniform driver behavior;
- Increase trip reliability;
- Delay onset of freeway breakdown;
- Reduction in traffic noise;
- Reduction in emissions; and
- Reduction in fuel consumption.

Guidelines for Queue Warning

The basic principle of queue warning is to inform travelers of the presence of upstream queues, based on dynamic traffic detection and using warning signs and flashing lights. This strategy allows the traveler to anticipate a situation of emergency braking and limit the extent of speed differentials, erratic behavior, and queuing-related collisions. Queue warning can be used on its own with DMS placed on overhead gantries that show the symbol or word when a queue is close. It can also be included with speed harmonization and lane control signals to provide incident management capabilities. The system can be automated or controlled by a TMC operator. Work zones also benefit from queue warning with portable DMS units rightfully placed upstream of expected queue points.

Data Needs

At a minimum, the following data are necessary for successful implementation of queue warning:

- Traffic volumes;
- Travel speeds; and
- Incident presence and location.

Essential and Preferable Elements

General criteria for queue warning include the following:

- Essential criteria:
  - LOS E/F for at least 2 hours per peak period;
  - Presence of queues in predictable locations;
  - Sight distance restricted by vertical grades, horizontal curves, or inadequate illumination;
  - Right of way for overhead gantries and DMS; and
  - At least five incidents related to queuing merging and diverging per week.
- Desirable criteria:
  - Large mix of high profile vehicles or inability to control speeds;
  - Willingness to automate the deployment of strategy; and
  - Existing ITS and connections to TMC.

Key Factors

The following are key factors to consider that can help facilitate successful deployment:

- Queue warning can be more effective when deployed in conjunction with speed harmonization.
- When implemented with speed harmonization, the queue warning pictograms and/or flashing lights need to be visible to all vehicles. During normal operation, all the signs are blank. The signage should also be consistent and uniform to clearly indicate congestion ahead.
- An expert system that deploys the strategy based on prevailing roadway conditions without requiring operator intervention is optimal.

Potential Benefits and Impacts

The following are potential benefit and impacts of queue warning, depending on local conditions and deployment approach:

- Decrease in primary incidents;
- Decrease in secondary incidents;
- Decrease in incident severity;
- More uniform speeds;
- Decreased headways;
- More uniform driver behavior;
- Increased trip reliability;
- Reduction in traffic noise;

- Reduction in emissions; and
- Reduction in fuel consumption.

Guidelines for Dynamic Merge Control

Dynamic merge control, or junction control, is used to dynamically meter or close specific lanes upstream of the interchange to manage access based on traffic demand (1). It is an operational treatment that addresses the geometric condition when the sum of both freeway general purpose lanes and merging lanes at an interchange is higher than the number of downstream general purpose lanes. A typical U.S. application of this condition would be a lane drop for one of the outside lanes or a merging of two inside lanes, both of which are static solutions. The intent is to provide dynamic priority access to the higher traffic stream. Dynamic merge control can be a permanent application, or it can be used temporarily until a downstream roadway is widened (*35*). It is a practical approach to handling varying demand on the main lanes and the merging lanes to effectively utilize existing capacity.

Data Needs

At a minimum, the following data are necessary for successful implementation of dynamic merge control:

- Maximum capacity of upstream general purpose lanes;
- Traffic volumes on general purpose lanes and merging ramps;
- Travel speeds on general purpose lanes and merging ramps; and
- Incident presence and location.

Essential and Preferable Elements

General criteria for dynamic merge control include the following:

- Essential criteria:
  - Significant merging volumes (>900 vph);
  - Available capacity on general purpose lanes upstream of the interchange that can be borrowed with no worse than LOS E after implementation; and
  - Non-simultaneous peak traffic upstream on the general purpose lanes and merging lanes.

- Preferable elements to dynamic merge control:
  - Active incident management in the corridor;
  - Existing ITS and connections to the TMC; and
  - Combination with shoulder use.

Key Factors

The following are key factors to consider that can help facilitate successful deployment:

- Effective dynamic merge control uses lane control signals on the main lanes and merging lanes of a freeway to dynamically adapt to varying demand. It is important that these signs be installed on gantries that are sufficient enough to ensure advance warning to roadway users.

- An expert system that deploys the strategy based on prevailing roadway conditions without requiring operator intervention is optimal.
- To handle emergencies, a bypass lane for emergency vehicles, transit, or other identified exempt users is optimal.
- Dynamic merge control can be implemented in conjunction with temporary shoulder use as long as the overhead gantries with appropriate signing and lane control signals are part of the implementation.

Potential Benefits and Impacts

The following are potential benefit and impacts of dynamic merge control, depending on local conditions and deployment approach:

- Increased throughput;
- Increased capacity;
- Decrease in primary incidents;
- More uniform speeds;
- More uniform driver behavior; and
- Increased trip reliability.

Guidelines for Dynamic Rerouting and Traveler Information

Dynamic rerouting and traveler information are the practice of redirecting traffic to avoid unequal levels on service on parallel routes. The intent is to provide users with viable route alternatives, and the approach can be especially beneficial in helping reduce the impact of noncurrent congestion. A new direction can be suggested while the standard routing remains, or if the hardware allows it, the standard routing may be substituted by the recommended one. Both of these strategies require some sort of DMS, either a full size sign or smaller ones embedded into common route signs. When the main road is congested, rerouting traffic on a parallel road to relieve further congestion can be an efficient strategy. The implementation can be automated, but needs to include detailed information about both roads, such as short range expected volumes, construction, or special events.

When considering dynamic rerouting and traveler information, there are two signing strategies that can be applied: substitution and addition.

- *Substitution:* In the substitution strategy, rotating panels on guide signs turn and indicate the suggested secondary route. The problem encountered with this method is that the first route is no longer displayed, and some mid-trip destinations may be missed.
- *Addition:* In the addition strategy, orange arrows show the recommended diversion route while keeping the original signing. In both cases, full matrix DMS can be used to display any of those strategies.

Data Needs

At a minimum, the following data are necessary for successful implementation of dynamic rerouting:

- Traffic volumes;
- Travel speeds;
- Weather conditions;
- Incident presence and locations; and
- Conditions and availability of alternate routes.

Essential and Preferable Elements

General criteria for dynamic rerouting and traveler information include the following:

- Essential elements:
    - LOS E or F for 2 hours per day;
    - At least 3 incidents per week resulting in severe congestion;
    - Viable parallel corridor to accept rerouted traffic no farther than 2 mi from primary corridor;
    - Available capacity on parallel route; and
    - Available right of way for overhead gantries if necessary.

- Preferable elements:
    - Existing ITS and connections to the TMC; and
    - Combination with speed harmonization and temporary shoulder use.

Key Factors

The following are key factors to consider that can help facilitate successful deployment:

- The implementing agency needs to make a commitment to providing alternate route information to roadway users in response to nonrecurrent congestion.
- Dynamic rerouting and traveler information can be more effective when deployed in conjunction with speed harmonization and temporary shoulder use.
- The agency needs to ensure that there is an adequate installation of sign gantries along the facility at critical locations to ensure that sufficient advance notice of alternate routes is provided.
- Dynamic rerouting and traveler information are most effective when connectivity to adjoining TMCs exists to coordinate alternate route information based on roadway conditions and special events in adjoining regions. Coordination with local communities to minimize the impact of alternate route information on the arterial network is also important.

Potential Benefits and Impacts

The following are potential benefit and impacts of dynamic rerouting and traveler information, depending on local conditions and deployment approach:

- Increased throughput;
- Decrease in primary incidents;

- Decrease in secondary incidents;
- More uniform driver behavior; and
- Increased trip reliability.

Guidelines for Dynamic Truck Restrictions

Dynamic truck restrictions require all truck traffic to use designated lanes in a dynamic manner during peak periods. The intent is to increase the homogeneity of speed on each lane and to minimize the disruption in traffic flow caused by heavy vehicles. The dynamic nature of the treatment allows for more flexibility in application as opposed to static restrictions. The activation of the signs indicating the presence of restrictions is usually automated and is triggered by real-time traffic volumes. The signs should be placed on overhead gantries for visibility.

Data Needs

At a minimum, the following data are necessary for successful implementation of dynamic truck restrictions:

- Traffic volumes, including truck volumes;
- Travel speeds;
- Weather conditions; and
- Incident presence and locations.

Essential and Preferable Elements

General criteria for speed harmonization include the following:

- Essential elements:
    - Significant proportion of truck traffic;
    - Available right of way for overhead gantries; and
    - No left side exits in the controlled section.

- Preferable elements:
    - Existing ITS and connections to the TMC; and
    - Combination with speed harmonization.

Key Factors

The following are key factors to consider that can help facilitate successful deployment:

- Agencies will need to seek enabling legislation and related laws to allow dynamic truck restrictions.
- An expert system that deploys the strategy based on prevailing roadway conditions without requiring operator intervention is ideal. It is very important that this expert system by reliable and accurate in order to gain the trust and acceptance by system users.
- The installation of sign gantries needs to be sufficient to ensure that at least one sign displaying the restrictions is visible at all times.

Potential Benefits and Impacts

The following are potential benefit and impacts of dynamic truck restrictions, depending on local conditions and deployment approach:

- Increased throughput;
- Increased capacity;
- More uniform speeds;
- More uniform driver behavior;
- Increased trip reliability;
- Reduction in emissions; and
- Reduction in fuel consumption.

Chapter 4: Final Remarks

It is the hope of the authors that by providing transportation agencies with information on practices for deployment and operation of TM strategies as well as general guidance on implementation, that this document can have a positive impact on transportation networks where ATM is feasible. Potential improvements can include:

- An increase in average throughput for congested periods;
- An increase in overall capacity;
- A decrease in primary accidents;
- A decrease in secondary accidents;
- A decrease in accident severity;
- An overall harmonization of speeds during congested periods;
- An increase in trip reliability; and
- The ability to delay the onset of freeway breakdown.

ATM has the potential to help transportation agencies address the ever-increasing challenge of doing more with less and operating existing facilities in the most efficient manner possible.

References

1. Mirshahi, M., J. Obenberger, C. Fuhs, C. Howard, R. Krammes, B. Kuhn, R. Mayhew, M. Moore, K. Sahebjam, C. Stone, and J. Yung. *Active Traffic Management: The Next Step in Congestion Management*. Report No. FHWA-PL-07-012. Alexandria, VA: American Trade Initiatives for Federal Highways Administration. 2007.

2. TRB Joint Subcommittee on Active Traffic Management—AHB20(5). *Definition of Active Traffic Management*. Unpublished Committee Document. Washington, DC: Transportation Research Board. 2009.

3. Grant, D. *M42 Active Traffic Management Pilot Project.* Unpublished Presentation to Planning for Congestion Management Scan Team. London, England: Highways Agency, Department for Transport. June 2006.

4. *Active Traffic Management (ATM) Project M42 Junctions 3A-7.* London, England: Highways Agency, Department for Transportation. http://www.highways.gov.uk/knowledge/tcc/atm/index.htm. Accessed May 2011.

5. *Advanced Motorway Signaling and Traffic Management Feasibility Study.* London, England: Department for Transport. 2008.

6. *M42 Active Traffic Management Results—First Six Months.* London, England: Highways Agency, Department for Transport. 2007.

7. *4-Lane Variable Mandatory Speed Limits—12 Month Report.* London, England: Highways Agency, Department for Transport. 2008.

8. Lemke, K., and M. Irzik. *Temporary Use of Hard Shoulders—Experiences and Economic Assessment.* Presentation to Planning for Congestion Management Scan Team. Bergisch Gladbach, Germany: Federal Highway Research Institute, Traffic Planning, Highway Design, and Safety Analyses Section. June 2006. Original photos courtesy of Autobahndirektion Sudbayern (South Bavaria).

9. Riegelhuth, A., and A. Pilz. *ERP Achievements and Results in Traffic Management—Temporary Hard Shoulder Use in Hessen—Experiences and Strategic Planning.* Hessen, Germany: Traffic Centre Hessen (CENTRICO). June 2007.

10. Helleman, B. *Hard Shoulder Running (HSR) in the Netherlands.* Presentation to Planning for Congestion Management Scan Team. Rotterdam, The Netherlands: Ministry for Transport, Public Works, and Water Management, Directorate-General of Public Works and Water Management, AVV Transport Research Centre. June 2006.

11. *Rush Hour Lanes.* Ministry of Transport, Public Works and Water Management, www.verkeerenwaterstaat.nl, 04/17/2003, accessed 10/31/2005.

12. Middelham, F. *Dynamic Traffic Management.* Presentation to Planning for Congestion Management Scan Team, Rotterdam, The Netherlands: Ministry of Transport, Public Works, and Water Management, Directorate-General of Public Works and Water Management. AVV Transport Research Centre, June 2006.

13. Martin, P. *Bus Use of Shoulders.* TCRP Synthesis 64. Washington, DC: Transportation Research Board. 2006.

14. Kuhn, B. *Efficient Use of Highway Capacity Summary.* Report No. FHWA-HOP-10-023. College Station, TX: Texas Transportation Institute, The Texas A&M University System. 2010.

15. McCasland, W.R. Use of Freeway Shoulders to Increase Capacity. In *Transportation Research Record 966*. Washington, DC: Transportation Research Board, National Academies of Science, 1978.

16. Curren, J. *Use of Shoulder and Narrow Lanes to Increase Freeway Capacity*. NCHRP Report 369. Washington, DC: Transportation Research Board, 1995.

17. Ungemah, D., and B. Kuhn. *Strategy Screening Criteria for Managed Use Lane Projects.* Report for New York State Department of Transportation. College Station, TX: Texas Transportation Institute and Parsons Brinckerhoff. July 2008.

18. *Summary of Accident and Vehicle Breakdown Data Related o Inside Shoulders, Houston, Texas.* College Station, TX: Texas Transportation Institute, The Texas A&M University System. 1986.

19. Urbanik, T., and C. Bonilla. California Experience with Inside Shoulder Removals. In *Transportation Research Record 1122*. Washington, DC: Transportation Research Board, National Academy of Science. 1987.

20. *Active Traffic Management Feasibility Study.* Report to Washington State Department of Transportation, Urban Corridors Office. Seattle, WA: PB Americas, Carter + Burgess, EarthTech, Inc., and Telvent Farradyne. 2007.

21. *Guidelines on Shoulder Use by Buses.* Minneapolis, MN: Minnesota Department of Transportation, Metro Division. 1997. http://www.dot.state.mn.us/metro/teamtransit/docs/bus_only_shoulder_guidelines.pdf, Accessed 2011.

22. Martin, P. *Bus Use of Shoulders.* TCRP Synthesis 64. Washington, DC: Transportation Research Board. 2006.

23. Thomsom, R. "Virginia Extending Shoulder Use on I-66." In *The Washington Post*. Washington, DC: August 8, 2008. http://voices.washingtonpost.com/getthere/2008/08/to_accommodate_increased_traff.html. Accessed June 2011.

24. Miles, J., and W. Broeders. *Evaluation of the Finnish AINO Programme 2004-2007.* Helsinki, Finland: Ministry of Transport and Communications. 2007.

25. *FHWA Scanning Report on Traffic Management and Traveler Information Systems.* Report No. FHWA-PL-98-010. Alexandria, VA: American Trade Initiatives for Federal Highway Administration, 1997.

26. Coleman, J., J. Paniati, R. Cotton, R. Covey, D. Graham, J. McCauley, G. Mortford, J. Paniati, M. Parker, H. Pena, and M. Robinson, W. Taylor. *FHWA Study Tour for Speed Management and Enforcement Technology*. Report No. FHWA-PL-96-006. Alexandria, VA: American Trade Initiatives for Federal Highway Administration. 1995.

27. Rämä, Pirkko. *Effects of weather-controlled variable message signing on driver behavior*. VTT Publications No. 447. Helsinki, Finland: Technical Research Centre of Finland, VTT Building and Transport. 2001.

28. Kuhn, B. *PCM International Scan Tour—Netherlands.* Rotterdam, Netherlands: Unpublished Personal Notes. June 2006.

29. Kuhn, B. *PCM International Scan Tour—England.* London, England: Unpublished Personal Notes. June 2006.

30. *M25 Controlled Motorways Summary Report, Issue 1.* London, England: Highways Agency, Department for Transport. 2004.

31. Steinke, D., L. Sanderson, J. Byrnes, J. Conrad, R. Forrestel, K. Harrington-Hughes, K. Kobetsky, S. Lanford, K. Snyder-Petty, D. Testa, and J. Wilkerson. *Methods and Procedures to Reduce Motorist Delays in European Work Zones.* Repot No. FHWA-PL-00-001. Alexandria, VA: American Trade Initiatives for Federal Highway Administration. 2000.

32. Kuhn, B. *PCM International Scan Tour—Denmark.* Copenhagen, Denmark: Unpublished Personal Notes. June 2006.

33. *Smarter Highways.* WSDOT Website. http://www.wsdot.wa.gov/smarterhighways/vsl.htm. Accessed June 2011.

34. "Missouri Activates Variable Speed Trap Program." On *theNewspaper.com.* http://www.thenewspaper.com/news/23/2386.asp, May 2008.

35. Tignor, S., L. Brown, J. Butner, R. Cunard, S. Davis, G. Hawkins, E. Fischer, M. Kehril, P. Rusch, and S. Wainwright. *Innovative Traffic Control—Technology and Practice in Europe.* Report No. FHWA-PL-00-021. Alexandria, VA: American Trade Initiatives for Federal Highway Administration. 1999.

36. Njord, J., J. Peters, M. Freitas, B. Warner, K. Allred, R. Bertini, R. Bryant, R. Callan, M. Knopp, L. Knowlton, C. Lopez, and T. Warne. *Safety Applications of Intelligent Transportation Systems in Europe and Japan.* Report No. FHWA-PL-06-001. Alexandria, VA: American Trade Initiatives for Federal Highway Administration. 2006.

37. "Good Traffic Management Techniques Know No Bounds." In *TranScan*, No 3. Washington, DC: National Cooperative Highway Research Program, TRB. 2001.

38. Bolte, F. *Transport Policy Objectives: Traffic Management as Suitable Tool.* Presentation to Planning for Congestion Management Scan Team. Bergisch-Gladbach, Germany: Federal Highway Research Institute (BASt). 2006.

39. Jarema, F., C. Dahlin, R. Gillmann, M. Hallenbeck, D. Huft, R. Reel, and R. Tweedie. *FHWA Study Tour for European Traffic-Monitoring Programs and Technologies.* Alexandria, VA: American Trade Initiatives for Federal Highway Administration. 1997.

40. Toole, O. *Trucks on Motorways in the Netherlands—A Survey of the Role of Trucks in Traffic Flow.* Presentation to Planning for Congestion Management Scan Team. Ministry for Transport, Public Works, and Water Management, Directorate-General of Public Works and Water Management, AVV Transport Research Centre. June 2006.

41. McCarthy, K. *Trucks-Speed Limits and Lane Restrictions.* OLR Research Report No. 2005-R-0814, 2005.

42. *M5 Junctions 19 to 20 Pilot Scheme—Advisory Restrictions for Towing Vehicles.* London, England: Highways Agency, Department for Transport. 2005.

UTCM

University Transportation Center for Mobility™

Texas Transportation Institute

The Texas A&M University System

College Station, TX 77843-3135

Tel: 979.845.2538 Fax: 979.845.9761

utcm.tamu.edu

Texas Transportation Institute