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16. Abstract

Traffic congestion is an increasing problem in the nation's urban areas, leading to personal inconvenience, increased pollution, hampered economic productivity, and reduced quality of life. While traffic congestion tends to continuously increase, growth in transportation infrastructure is limited by financial and land availability constraints. This has placed an increasing emphasis on using dynamic traffic management strategies, such as speed harmonization and peak-period shoulder use, to efficiently manage congestion using existing freeway capacity. This project implemented various strategies of variable speed limits and shoulder use and assessed their impact on traffic operations and safety of freeway. These strategies were found to homogenize traffic and create safer driving conditions, but did not increase the throughput of the system. The ITS devices required to implement these strategies, enforcement issues, potential impediments in their implementations, and a framework for cost-benefit analysis to determine the economic viability are also discussed.

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Speed Harmonization and Peak-period Shoulder Use to Manage Urban Freeway Congestion

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Chapter 1. Introduction

1.1 Motivation

Traffic congestion is an increasing problem in the nation's urban areas leading to personal inconvenience, increased pollution, hampered economic productivity, and reduced quality of life. With continuous additions to capacity no longer a feasible option, an increasing emphasis has been placed on developing innovative dynamic traffic management strategies for efficient usage of existing freeway infrastructure capacity. Dynamic Traffic Management (DTM) initiatives facilitate the management of recurrent and non-recurrent congestion by monitoring and controlling traffic in real-time.

The focus of this research is to assess the feasibility of implementing two specific DTM strategies in Texas: speed harmonization and peak-period shoulder use. Speed harmonization involves dynamic changes of speed limits at specific points on a freeway, based on prevailing traffic and/or weather conditions. Peak-period shoulder use allows for the temporary utilization of the shoulder as a running lane. Both techniques have been widely implemented in Europe and, to some extent, in the United States. The positive results obtained from such implementations, including accident rate reductions of up to 30% [1] and congestion reduction of 40% [2], warrant the need for this study. Additional benefits to be expected from these techniques include improved safety due to more homogenous speeds and uniform headways, decline in emissions, and improvements in travel time reliability [3]. By improving the reliability of the traffic management strategies and orienting them to address drivers' needs, it is possible to gain driver's trust and valuable cooperation in the solution of congestion problems. These are the primary features of customer-based services, a concept increasingly becoming popular in Europe [4].

Even though speed harmonization and peak-period shoulder lane usage have been implemented widely in Europe, and to some extent in the United States, there is not a unified methodological approach to select implementation parameters (speed limits, intervention triggers, and duration of intervention). Moreover, some significant differences between European and US freeways, including geometric design, ITS infrastructure, and driver behavior, warrant a careful and systematic analysis of additional implementation and institutional issues. This study will investigate the suitability of speed harmonization and peak-period shoulder usage in Texas freeways by addressing institutional, operational, and methodological challenges. This will provide the tools to perform a proper cost-benefit analysis, leading to a realistic implementation decision.

(i) Institutional Challenges: The focus of this research module will be on understanding organizational responsibilities in terms of data collection, archiving policies, and enforcement. Data requirements will be studied and recommendations will be provided as well. In addition to this, the proposed research will analyze the type of inter-agency coordination needed, including interactions with local media and police force, for enforcement. Texas has delegated the speed limit enforcement to the Transportation Commission. Hines and McDaniel [5] found that the statute by means of which Texas delegated the speed limit enforcement authority appeared appropriate for the implementation of variable speed limits (VSL). However, a revision of the principal features of this law may be necessary to verify its adequacy to support the implementation of particular enforcement technologies, and of peak period shoulder usage. This research will identify possible institutional impediments to a successful deployment of speed harmonization and peak-period shoulder lane usage, and suggest appropriate solutions. Past experiences in USA and Europe will be considered, and interviews conducted when appropriate.

(ii) Methodological Challenges: This research module will focus on the control algorithms to be run in the computer system of traffic management centers, and on identifying performance metrics to evaluate the performance of different control strategies, which will be tested using simulation models. A multi-resolution simulation platform will be constructed. Under such a platform the local freeway/arterial impacts will be determined using a microscopic simulator, whereas a mesoscopic simulator will provide the network level impacts.

(iii) Operational challenges: The focus of this research module will be on identifying the traffic engineering issues related to the deployment of speed harmonization and peak-period shoulder usage. These include geometric and structural design of shoulder lane elements, safety considerations, and Intelligent Transportation Systems (ITS) infrastructure requirements. ITS technology will be evaluated for several purposes, including surveillance, lane management, information dissemination, and enforcement. Existing technologies will be explored, and their advantages, costs, and availability carefully assessed. Additionally, recommendations for the potential need to design appropriate signaling devices will be provided if necessary. This module will also review the infrastructure requirements for a successful and safe operation of shoulder lanes as regular running lanes. These include minimum width, structural design, and the provision of additional emergency refuge areas. Figure 1.1 presents a graphical summary of the above discussion.

1.2 Outline of this Report

The remainder of this report is as follows. In Chapter 2 we present a collection of representative past experiences with speed harmonization and peak-period shoulder use. Chapter 3 introduces a multi-resolution framework to evaluate the dynamic traffic management strategies. Control strategies for speed harmonization are discussed in Chapter 4. Chapter 5 discusses the control strategies for peak-period shoulder use and provides some guidelines regarding the design of shoulders in light of speed harmonization and peak-period shoulder use. In Chapter 6 we identify crash precursors to assess the safety of these advanced traffic management strategies. Recommendations on ITS and enforcement issues and a discussion of potential impediments are provided in Chapter 7. Chapter 8 presents a comprehensive feasibility analysis framework and it also discusses an operational deployment plan. Finally, Chapter 9 provides some concluding remarks.

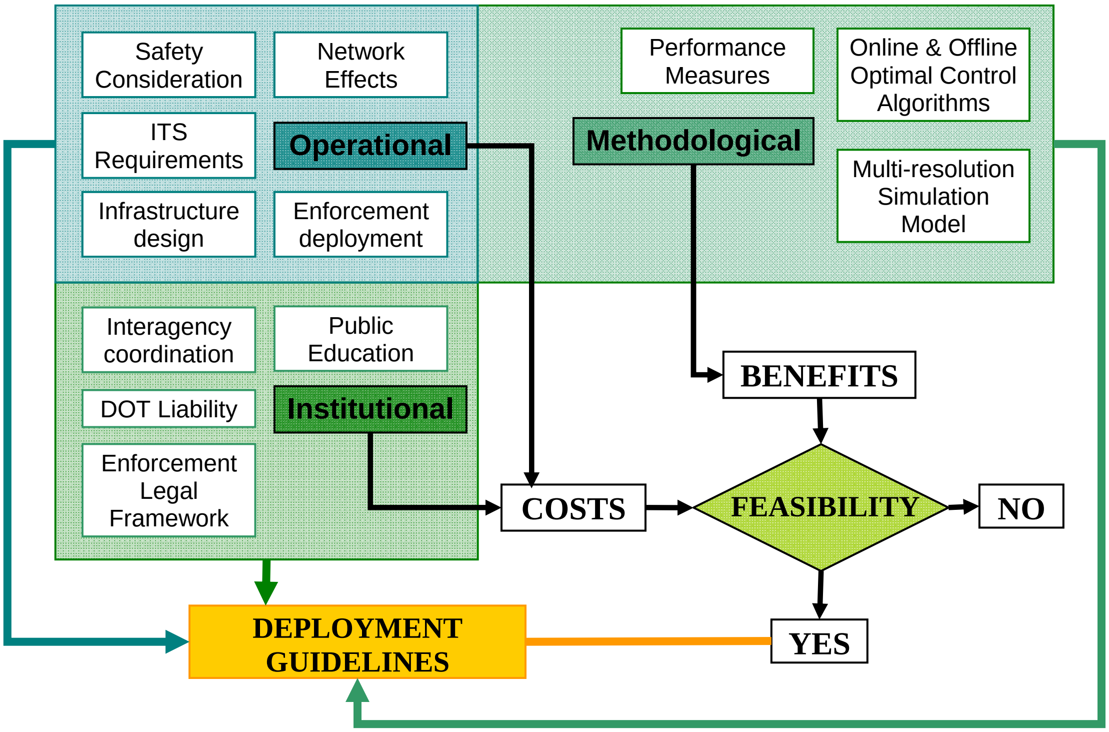


Figure 1.1: Research Framework

Chapter 2. Past Experiences with Speed Harmonization and Peak-period Shoulder Use

2.1 Speed Harmonization

Speed harmonization has been implemented in the past with various objectives, including postponement or prevention of the onset of congestion (United Kingdom), safety improvement (Germany), homogenization of traffic speeds in space and time (the Netherlands), freeway throughput augmentation, and pollution reduction. Previous experiences indicate that the strategy has been reasonably successful in achieving its objectives. For example, a case study in Germany found a 14% to 37% lower injury accident rate per vehicle-km in controlled highways [1]. The implementation of speed harmonization reduces the speed differential between and within lanes, and creates a more uniform and acceptable headway distribution thus reducing the potential for the occurrence of primary accidents [6]. Moreover, speed harmonization leads to more stable traffic flow and reliable travel times, and the decline in the amount of stop-and-go traffic can result in significant air quality benefits [7].

Successful implementation of speed harmonization typically requires a relatively dense ITS deployment, and efficient enforcement policies. Additionally, the development of appropriate control strategies for the selection of speed limits plays a fundamental role in the effectiveness of speed harmonization. The following sections describe some of the past experiences with speed harmonization implementation, and discuss issues related to the selection of control strategies. A more technical analysis of the speed limit selection process is presented in the next chapter.

2.1.1 Weather-controlled speed limits (Finland)

The objective of this study (Rama [8]) was to investigate the effects of weather-controlled speed limits on the mean speed and average headways. More specifically, it aimed to examine whether such speed limits contribute to increased traffic safety. The speed limits were displayed using variable message signs (VMS); speed and headway data were collected using loop detectors.

Interesting outcomes of the study include the following:

- An increase in the speed limits during favorable road and weather conditions increased the mean speed levels.
- A decrease in the speed limits during adverse weather conditions reduced the mean speed and increased the average headway, which is desirable for traffic safety.
- The mean speed under favorable roadway conditions was reduced, while it was increased during normal and adverse road and weather conditions. This latter can be attributed to lack of driver education: people tend to drive slowly during poor weather conditions, but because of a lack of understanding of the displayed speed limits—drivers thought of them as recommended values rather than maximum values—people will end up driving faster than average.
- Speed and friction measurements indicated that the observed values were in agreement with the ones prescribed on the VMS in 76% of the cases.

- Around 96% of the drivers considered variable speed limits (VSL) based on real-time weather and road conditions to be useful.
- People thought that VMS are easier to notice than conventional static signs.
- Most drivers were not aware that the VMS were displayed based on a control strategy. If this information were known to them, there might be some potential to improve the effect of VSL.

2.1.2 M25 Motorway (UK)

The primary objective of a 1995 speed harmonization project on the M25 Motorway (Figure 2.1) was congestion management. Additional objectives were the creation of a more comfortable driving experience and the reduction of fuel consumption. The motorway was instrumented with dual loop detectors spaced every 500 m (0.3 miles) that provided speed, volume, and occupancy data. When volumes reached 1,650 vehicles per hour per lane (vphpl), the speed limit was reduced from the default value of 70 mph to 60 mph. When volumes reached 2050 vphpl, the speed limit is further reduced to 50 mph. Among the observed benefits were the following:

- Reduction of the number of collisions by over 10%.
- During weekdays, travel times were reduced in one direction of the motorway.
- The controlled motorway has contributed to a more reliable journey time.
- A uniform distribution of traffic across all the four lanes was observed.
- A uniform headway distribution was observed.
- Reduced emission and noise levels.
- More comfortable driving experience.

As noted above, travel times in only one direction were observed to decrease. In fact, travel times in the other direction were increased. This can be partly attributed to the lesser amount of flow in this latter direction. Travel times were also found to increase in the off-peak periods. However, this is not due to speed limit reductions, but rather to the stricter enforcement measures that were necessary for compliance (Harbord and Jones [9]).

Figure 2.1: Speed Harmonization on M25, UK. Source: Warren [10]

More on the M25 Motorway: Results from the first 2 years (UK)

Based on initial studies it was found that implementation using traditional message signs that were manually changed by the police didn't provide the desired results. Thus this pilot used a more responsive system, automatically controlled and with mandatory speed limits. The enforcement system was also automatic, using wet-film cameras to take pictures of vehicles. Speed control was provided with the aid of the MIDAS (Motorway Incident Detection and Automatic Signaling) system. Speeds ranging from 20 to 60 mph were displayed. A red ring was used to indicate that the speed limits were mandatory. Statistical information provided by MIDAS was used to detect areas where enforcement could be more beneficial. A pre-set delay between the new speed limit and its enforcement was maintained, to allow for a safe change of speed [11].

Detectors were located every 500 m (0.3 miles) in all lanes. Data was processed by roadside stations to detect queues and slow moving traffic. Speed control was exercised when flow break down was about to occur. The initial implementation utilized fixed speed limits selected based on the time of the day. Later on, a dynamic control scheme that was based on simple flow thresholds sets the speed limit to be either 50 mph or 60 mph. Because the system was based on flow values, it was unable to detect when flow was reduced due to very low speeds, which caused the system to display high speed limits when traffic was stopped. Turning off the control system when congestion was set was considered, but drivers indicated that they preferred the limits to continue to be displayed.

During the course of the pilot, a new feature to protect drivers at the end of a queue was added. The HIOCC (high occupancy) algorithm was implemented to detect queues and slow moving traffic. The system typically set speed limits of 40 mph on the section immediately prior to the end of the queue (and 50-60 mph prior to this 40 mph section).

Important observations from this study were the following:

- Speed measurement using some other equipment, e.g., laser, was recommended instead of radar technology.
- Analysis of data suggested that speeds did not change when they were suggested; they had to be enforced. After enforcement, compliance was very high.
- The number of drivers exceeding the speed limit diminished by 50%. However, it was noticed that if traffic limits were posted more than 1 km (0.6 mile) apart (such that only one speed limit is visible at a time), drivers were found to speed between the gantries.

- Less lane changing was observed. Drivers did not see the point of changing lanes when everyone was driving at the same speed.
- Flow in the slow lane increased by 15%. More uniform and less extreme headways were observed.
- Injury accidents were reduced by 28%. This result was significant at a 95% confidence level, but it might have been influenced by roadwork.
- 60% of the drivers were happy with the system, and the fact that they could drive at a constant speed without worrying about changing lanes made them more comfortable.
- Travel time reduction could not be assessed with statistical significance. However, data suggested that the travel times were improved and their variability reduced.
- A 5% increase in traffic demand was observed during the pilot project, which was accommodated without increasing congestion.

2.1.3 A2 Motorway (The Netherlands)

The primary objective of the project was to reduce inefficiencies in lane utilization and speed differentials between lanes [12; 13]. A control strategy was developed to homogenize traffic flow by encouraging more uniform lane usage and less speed differential between lanes. Based on speed and volume data collected at dual loop detector stations every 500 m (0.3 mile), the displayed speed limit could potentially be reduced to 90 km/h (56 mph) or 70 km/h (43 mph) from the standard speed limit of 120 km/h (75 mph). Speed limits were only changed when volumes approached capacity. The choice of the speed limit is made every minute, based on measurements of the average traffic speed on the section under study. The goal is to keep the difference between the average speed and the limit speed as small as possible. The objective of the system was not to reduce average speeds, but to reduce speed differences within and between lanes.

Important observations include the following:

- Over 1,300 drivers were asked how they experienced the system and whether it had influenced their driving behavior. A large majority said they had adjusted their behavior due to the speed control measure.
- A large majority said they had benefited from the measure. Among the benefits cited were improved traffic flow and a less hectic driving experience. Furthermore, VSL had a warning effect regarding congestion and unsafe situations.
- One in five respondents was unfamiliar with the purpose of the speed signaling devices. Awareness of these devices has been found to have a positive impact on the extent to which drivers adjust to the new speed limit.
- Analyses showed that VSL created more homogeneous traffic: fewer speed variations, small headways, and shockwaves. Homogeneity was also achieved across lanes.
- The average speed on the motorway dropped while the average occupancy increased.
- No positive effect on the capacity could be demonstrated.

- A second evaluation performed six months after the start of the experiment showed that the effects of the speed control had decreased to some extent, but still remained positive.

2.1.4 State of Washington (USA)

In Ulfarsson et al. [14] speed harmonization was introduced to address the significant variations in speed due to the combined effects of vehicle mix, inclement weather, and challenging road geometrics. Based on environmental data and pavement conditions, speed limits were reduced from 105 km/h (65 mph) to as low as 56 km/h (35 mph) in 16 km/h (10 mph) decrements. Under conditions of high speed and low speed variations, it was found that the mean speed was reduced, while variations were more prevalent. On the other hand, under conditions of low speed and high speed variations, both mean speeds and speed variations were reduced. Hence this experiment shows that speed harmonization gives optimal effects only under certain traffic conditions.

2.1.5 Albuquerque, New Mexico (USA)

Speed harmonization was implemented on IH 40 (eastbound) in Albuquerque, New Mexico in 1989, with the main goal of minimizing accident risk and informing motorists of downstream hazards. Traffic data were collected from inductive loop detectors placed in each lane perpendicular to the roadside station equipment, at an average spacing of 1.5 miles. Loop data was collected every 10 seconds and processed to calculate speed, volume, length of vehicle and standard deviation of speed. A slight reduction in accident rates was reported [15].

2.1.6 VSL in work zones, Michigan (USA)

The VSL system was deployed during the summer of 2002 in a work zone on IH 96, south and west of Lansing, Michigan [16]. Prior to the deployment of the system on the actual site, it was tested on a local route. The following interactions between various institutions were found necessary during various stages of the project:

- The Department of Transportation and the State Police Department.
- The Department of Transportation and the Work Safe Department.
- The Department of Transportation and Michigan State University.

The Michigan Department of Transportation and the Michigan State Police have the legal authority to set speed limits in work zones within the state. According to the Michigan Vehicle Code,

> "a person operating a vehicle on a highway, when entering and passing through a designated work area where a normal lane or part of the lane of traffic has been closed due to highway construction, maintenance, or surveying activities, shall not exceed a speed of 45 miles per hour unless otherwise determined and posted by the state transportation department, a county road commission, or a local authority."

Two operational difficulties faced by the project personnel during the deployment of the project: 1) pneumatic tubes installed during the project were often ripped off by the traffic, leading to loss of data, and 2) there were communication problems between successive deployment sites and the remote access of these sites.

Among the conclusions of the project were the following:

- Increased average speeds.
- Reduction in travel times, although the reduction was not significant enough to be perceived by the drivers.
- Fewer drivers violated the speed limit;
- There was a positive response from the drivers to the speed limit changes.
- The installation of the VSL system did not cause any additional safety issues. Whether it increased the safety was not clear.
- It was concluded that VSL may have more utility in longer and simpler work zones. The reason for this is that in shorter and hectic work zones the flow of traffic would be dominated more by factors such as road geometrics.
- System technology needs to be improved before it can be widely used.

2.1.7 Experiments in Utrecht and Rotterdam, The Netherlands

The type of control strategy used was a simple homogenizing strategy developed by Van Toorenburg [17]. With this type of control an identical advisory speed limit is displayed for all lanes at a given set of consecutive signal stations at the same time (see Figure 2.2). The speed value is chosen out of a finite set and is in correspondence with the actual speed of the traffic stream. This will in almost all cases lead to a value of 90 km/h (50 mph), as this is about the mean speed when traffic reaches the road capacity. In some cases 80 or 70 km/h (50 or 43 mph) will be displayed. The only parameter left to optimize in this type of control is the time to change speed limits.

The motivation for this type of control is that congestion is caused by severe inhomogeneities of the traffic stream, which exist when the traffic volume approaches the capacity of the road, see Van Toorenburg [17]. It was concluded that exercising homogenizing control is advantageous in that it increases safety and reduces the probability of congestion.

Following are the conclusions from the field experiments:

- The instability of traffic flow—measured as the number of serious speed drops—significantly decreased with homogenizing control. The decrease that was measured amounted to about 50%.
- A small increase in the capacity was observed—1 to 2 %.
- No significant effects were measured in other traffic characteristics such as mean speed, speed differences, or distribution over lanes.
- No serious implementation problems were observed, indicating the relative ease of use and robustness of the control system.

Figure 2.2: Speed Harmonization in the Netherlands. Source: Warren [10]

2.1.8 Environmental Benefits of VSL—Austin, Texas (USA)

The motivation of this study is to reduce emissions. In a recent study by Wang and Walton [18], it was found that freeways and expressways traffic could generate over 40% of NO_x in a metropolitan area such as Austin, Texas. It is widely recognized that high speeds usually cause high vehicular emissions. These high speeds are usually experienced during the off-peak hours. Thus by controlling the speed during these off peak hours, emission reductions can be realized. The static speed limit on the IH 35 in Austin is 65 mph. In this experiment, the speed limit is reduced to 55 mph on certain "Ozone Action days."

Important conclusions from the experiment include the following:

- During off-peak hours, lowering the traffic speed through VSL leads to lower NOx emissions. Given the large contribution from freeway/expressway traffic to NOx emissions, a VSL strategy can be an effective measure to reduce NOx. By reducing the speed limit from 65 mph to 55 mph on "Ozone Action days," the average daily total NOx emission in a 24-hr period can be reduced by approximately 17 % on the selected IH 35 segment.
- Traffic flow and speed patterns are primary factors affecting the effectiveness of a VSL strategy. Before the deployment of a VSL, the flow and speed patterns of the selected freeway/expressway should be carefully investigated.
- Compared to fixed speed limits, the VSL strategy can be a promising way to balance travelers' need for mobility and the conservation of the environment.

2.2 Peak-period Shoulder Lane Use

According to the FHWA, 40% of the congestion in the United States is a result of insufficient capacity. Peak-period shoulder lane usage, also referred to as dynamic shoulder usage, is the temporary operation of hard shoulders as running lanes for normal traffic. It provides additional capacity when needed without major infrastructure expansion requirements. Previous experiences, such as the one described by Middelham [19], suggest that this dynamic lane management strategy can be extremely beneficial in alleviating congestion, as long as it is implemented in conjunction with appropriate measures to avoid deterioration in the overall highway safety. In effect, hard shoulders are usually narrower, and their use as a temporary running lane detracts from their function as a safety lane. As a consequence, measures including lower speed limits during shoulder operation, restrictions on the type of vehicles allowed into the shoulder, and restrictions on overtaking are usually enforced.

Even though the increased capacity provided by shoulder usage has the potential to alleviate congestion, the additional discharges from intervened sections may result in an overall deterioration of the network performance. This calls for a careful analysis of the network effects of peak-period shoulder usage before deployment. Cohen [20] describes a peak-period shoulder implementation focused on the removal of a bottleneck. The project achieved its goal, resulting in a 16% capacity improvement, and a 25% speed increase in the intervened section. Nevertheless, the additional flow discharges generated by the congestion removal led to worsened congestion downstream. This translated into increased travel times and recurring congestion between many origin-destination pairs in the corridor.

As for speed harmonization, peak-period shoulder usage techniques tend to require relatively intense ITS technology deployment. In the case of peak-period shoulder use, these are also used to discard the presence of detained vehicles, pedestrians, or dangerous debris in the shoulder before opening it to the traffic, and to ensure adequate safety conditions. Next we present a representative sample of past experiences with dynamic shoulder use.

2.2.1 Temporary Hard Shoulder on A5, Hessen (Germany)

The federal state of Hessen, Germany, implemented shoulder lane use, as well as other traffic management strategies, as part of their integrated intelligent transportation system. The temporary use of hard shoulders is controlled by the Traffic Center Hessen. Traffic volumes are monitored, and shoulder lanes become accessible when a certain threshold is crossed. Approximately 80 video cameras are used to monitor the shoulder lane to check for obstructions. The results were positive, as congestion was greatly reduced, and road safety suffered no negative changes:

- Improved traffic flow;
- Significant accident and congestion reduction;
- Capacity increase by 20%.

Because of these positive results, the state of Hessen plans to implement shoulder usage for congestion mitigation in more corridors in the future [21].

2.2.2 A3-A86 Junction, Paris (France)

Cohen [20] details the results of an experiment using the shoulder to increase the number of lanes (the hard shoulder was used to create a fifth lane in each direction). The experiment was implemented on the A3-A86 joint section in the Seine-Saint-Denis department north of Paris. It has to be noted that the change was not temporary but permanent. The system was controlled by the local Traffic Control Centre, and supervised 24 hours a day.

In order to deal with the induced safety issues, dynamic equipment was installed, including:

- Emergency call boxes;
- Variable Message Signs;
- Automatic Incident Detection.

The impacts on capacity, speed, and travel times were examined. In order to measure the impact on capacity, a measurement station was installed in the middle of the section with double loops providing the traffic flow rate, speed, and occupancy rate parameters. The data was gathered before and after opening the shoulder to regular traffic. The resulting capacity is shown in Table 2.1.

Table 2.1: Roadway capacity before and after opening of the shoulder lane to traffic

Lane	Capacity (veh/h)			
	Towards Paris		Towards Province	
	before	after	before	after
Right 1	2020	1335	2265	1865
Lane 2	2100	1635	1645	1750
Lane 3	1840	2040	2005	2000
Lane 4	2220	1755	2500	2035
Left 5		2390		2395
Section	*7890*	*8550*	*8100*	*9170*

The findings were that while capacity was increased, free flow speed did not change, and speeds during congested periods changed dramatically for certain origin-destination pairs. Similar results were obtained for the travel times. In fact, it was observed that for both the A3 and the A86 corridors there was increased congestion in at least one direction. With the opening of the hard shoulder, the bottleneck seemed to have moved.

2.2.3 M4, M25, and M42 (UK)

The British Highways Agency has developed an active traffic management (ATM) system, similar to the Dutch concept of dynamic traffic management, and is implementing it on a 16-km (10-mi) stretch of the M42 east of Birmingham in the West Midlands (Figure 2.3). While Britain has used variable speed control signs since 1964 and has been monitoring speeds and detecting incidents with its MIDAS system, closed-circuit cameras, and Trafficmaster™ APNR (photo billing and enforcement) systems for many years, the M42 combined these with new measures.

These innovations included use of the hard shoulder, as is done in the Netherlands, and new rapid response incident management practices borrowed from the United States. The purpose of the ATM pilot was to create more reliable travel times and congestion reduction, by providing drivers more and better traffic information and by responding more quickly to incidents.

Enforcement was realized via Automatic Number Plate Recognition (ANPR) camera. Furthermore, the Highways Agency traffic officers also had the power to stop traffic, close roads, direct traffic, and enforce laws. It was concluded that travel times were shorter, accident and emission rates declined, and speed compliance increased. Moreover, drivers' reactions were positive.

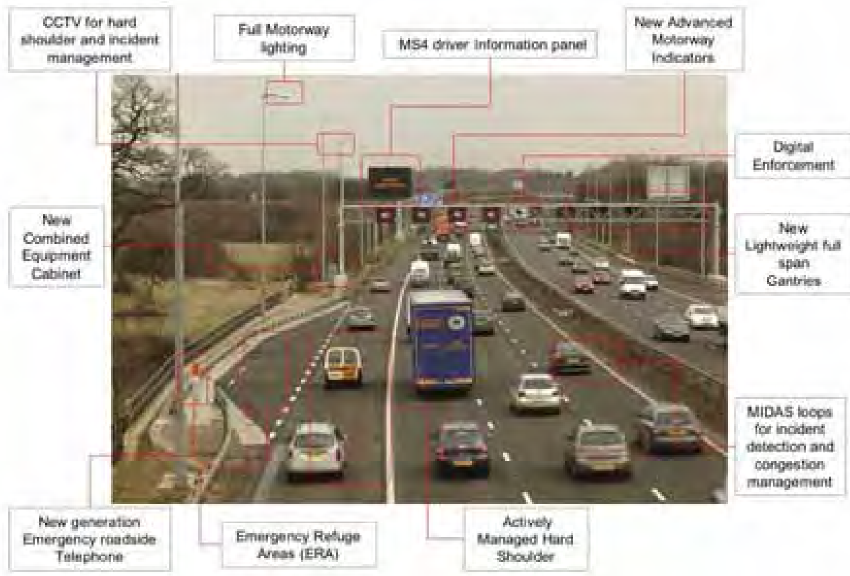


Figure 2.3: Active traffic management on M42

The Royal Society for the Prevention of Accidents [22], in a response to the highway agency statutory instrument consultation pack, reported on some issues resulting from the implementations of shoulder use employed in the past that would be relevant to the implementation on M42. The report mentions that early implementations in the US resulted in a higher number of collisions, but that sophisticated management strategies reduced this number. It also mentions that the opening of the shoulder lane is done regularly in the US during peak hours, whereas in the Netherlands traffic management centers only resort to this DTM strategy in case of heavy congestion. In the seven locations where it has been implemented in the Netherlands, emergency refuge areas have been implemented every 500 m (0.3 miles); they are equipped with MIDAS and phone services. Further, speed limits are strictly enforced and overtaking is restricted.

The main legal issue discussed in the report is the issue of keeping users from traveling in the hard shoulder beyond the specified time or space intervals.

Gaskell et al. [23] describes the use of hard shoulders as an additional running lane when incidents occur or during recurring congestion. The study focuses its concerns on safety and identifies the following as key elements to guarantee safety:

- Provision of emergency refuge areas (ERAs) at 500 m (0.3 mile) intervals
- Message signs at approximately every 500 m (0.3 mile) to provide clear instructions to drivers, i.e., speed limits and so on
- Enforcement of low speed limits (50 mph on all lanes)
- Refined monitoring system, involving loop detectors every 100 m (0.06 mile).

These monitoring systems are necessary because traffic operators need to be able to detect obstructions and incidents on the shoulder (e.g., pedestrians, debris, and slow moving cars) before the opening it as a running lane. Once the shoulder is opened to regular traffic, the main concern becomes the detection of incidents. The authors proposed to monitor via two types of sensors: loops (short range, high accuracy) and cameras (medium range and accuracy). The optimal spacing and location need to be determined and data fusion techniques should be developed to merge the information provided by the two sensor types.

2.2.4 DTM in the Netherlands

Middelham [19] claims that the use of shoulder lanes as rush hour lanes is justified because the technical characteristics of vehicles have improved tremendously. As such, vehicle break downs are less likely and hard shoulders are rarely used. In order to implement shoulder usage, the author recognizes the need for video monitoring, variable speed limits, and escape points. In three pilot test sites, the capacity increased by more than 50%; at the same time safety was increased as well. Guidelines for the layout of the control equipment have been developed [19]. More than 500 km (311 miles) of roadway are expected to be equipped with such equipment in the coming years.

2.2.5 Autostrada del Brennero - Highway A22 (Italy)

Bergmeister et al. [24] details a project in which an emergency lane is used to expand a two-lane facility when traffic demand exceeds or is near capacity. This project is of particular importance because it is being implemented on a 125-km (78-mile) stretch, which is the longest to date. The plan includes adjusting structures (e.g., including bridges, overpasses, and viaducts) to allow for the continuous running of the shoulder lane. The local Traffic Control Centre in charge of handling the managed lane gathers information from

- Traffic Sensors: 20 induction-loop stations;
- Cameras: 41 video cameras;
- Weather sensors: 14 sensors measuring wind, rain, ice, and visibility.

The VMS is used to control the speed of traffic, warn about congestion or treacherous conditions, direct traffic in the case of accidents, and deviate traffic for other reasons.

The biggest concern in this project was the management and control of transition conditions, i.e., opening and closing of the dynamic lane. In order to appropriately monitor the system and to determine when to open (close) the dynamic lane, gantries were located in 5-km (3-mile) intervals, containing detection and monitoring systems, variable message signs, and infraction detection devices. Cameras were located every kilometer to check roadway conditions before the opening (and after the closing) of the extra lane. Both the opening and closing of the dynamic lane is done on a per stretch basis. The speed of the traffic on adjacent lanes determines the opening (closing) of the emergency lane.

2.2.6 Hard Shoulders Usage in Germany

Kellermann [25] examines the steps necessary to open hard shoulders to traffic and the conditions under which such a measure is justifiable. General results suggest that opening shoulders has positive impacts on traffic quality and congestion. Safety concerns were addressed by implementing complementary measures, such as speed limits and other restrictions. The study identified the main function of hard shoulders as these:

- Area to leave damaged vehicles;
- Lateral space to use for avoidance maneuvers if unexpected obstacles appear on the road;
- Temporary traffic road if there are accidents on any of the main lanes;
- A place for maintenance crews to set up in order to perform work and winter maintenance;
- A place where emergency vehicles can run and where vehicles can be towed away.

In Germany, accident rates on roads without hard shoulders were found to be 25% higher than on those with hard shoulders. In general, opening hard shoulders to regular traffic should be considered as a temporary measure, unless speed limits can be enforced and refuge areas can be provided. The legal requirements depend on the type of implementation. If the hard shoulder is used temporarily, legislation regarding the use of the continuous white line will be required. Potential physical requirements identified by the study include the following:

- Shoulder reinforcement;
- Acceleration and deceleration lanes;
- Emergency stopping areas need to be provided;
- Drainage and slope requirements must be met.

The experiment showed that for permanently opened shoulder lanes a significant decrease in congestion (68-82%) was realized, as well as an increase in average speed (9%). As for safety, it is concluded that an emergency stopping lane is much more effective in reducing accidents than refuge areas.

For temporarily opened shoulder lanes, the number of accidents was reduced by half, if approach and exit sections were considered in addition to the highway segment. The temporary opening of shoulder lanes at pre-specified hours or at times of heavy congestion did not alter the overall accident rate: the number of congestion-induced accidents decreased, but the number of lane-changing accidents increased at the same time. Finally, the road maintenance cost increased because of the time limitations imposed by shoulder use on maintenance crews (maintenance crews could not operate during certain times of the day).

Chapter 3. A Multi-Resolution Simulation Framework

3.1 Toward a Simulation Model

The implementation of dynamic traffic management strategies such as speed harmonization and peak-period shoulder use necessitates a careful analysis to justify the associated high expenditures. Naturally, the most straightforward way to perform such analysis is the selection of a test corridor and the actual implementation of the strategies under consideration. However, due to financial reasons, this might not be feasible as dynamic traffic management strategies typically require extensive use of ITS. An alternative and economically viable way to perform such analysis is via traffic simulation.

Traffic simulation can be performed at various levels of detail: micro, meso, and macro. Each of these types of simulation has its own advantages and disadvantages. For instance, microsimulation tends to be the most accurate in modeling driver behavior (provided that the model is properly calibrated), but computationally challenging. On the other hand, mesoscopic simulation is less computationally intensive, at the expense of a less detailed modeling of driver behavior. In this report, we propose a hybrid traffic simulation approach to eliminate the above stated disadvantages. More specifically, we consider the combination of micro- and mesoscopic traffic modeling. Speed harmonization and peak-period shoulder use are typically implemented at a few specific sections of a road network, whereas their impacts can be felt far beyond these regions. Hence we conjecture that it is beneficial to perform a more detailed simulation study (i.e., microsimulation) at the sections where a dynamic traffic management strategy is being applied, whereas in order to capture network effects (and to maintain a reasonable computation time), a less detailed but sufficiently accurate simulation (i.e., mesoscopic simulation) can be performed for a larger network area.

The rest of this section is organized as follows. First, we provide a discussion of microsimulation modeling techniques. Then we examine its mesoscopic counterpart. The proposed multi-resolution approach is detailed thereafter, in which we provide a discussion on the way speed harmonization and peak-period shoulder use can be represented in a multi-resolution framework. We will also discuss possible performance measures.

3.1.1 Microscopic Modeling Techniques

Microsimulators model individual vehicles with a high degree of realism. This includes vehicle-specific lane changing and driving behavior, detailed signalization and gap acceptance models, and simulating at very small time intervals, often less than a second. In order to simulate the longitudinal and lateral movements of individual vehicles, microsimulators employ detailed car following and lane changing models. These models incorporate the human behavioral element of real traffic via the use of parameters. While a high level of detail is the key attraction of microsimulators, accounting for such detail requires calibration of a large number of parameters. Moreover, the model parameters are highly sensitive and often deliver misleading results if not chosen correctly. Therefore, proper calibration and validation is highly necessary when using microsimulation models, particularly in network analysis which can require extensive data collection. Accommodating this level of detail greatly increases the computation power needed, and microscopic analysis is typically confined to relatively small analysis zones and, hence, may give rise to boundary effects [26].

An alternative to the traditional, discrete time-step microsimulators are event-based simulators, such as that built into Dynameq [27]. In Dynameq, realistic but simplified traffic models can be calibrated very easily with only a handful of parameters, each with real-world significance. Thus, its event-based supply-side simulator provides an order of magnitude performance improvement over traditional time-step traffic microsimulation. As the traffic simulation is event-based, the traffic phenomena that trigger congestion are modeled explicitly, including signals, conflicting movements at intersections, lane permissions for turning movements and vehicle classes, and weaving.

Various microsimulation packages exist. Well-known commercially available microsimulation packages include, but are not limited to, CORSIM [28], VISSIM [29], and Paramics [30]. For a detailed description of these various alternatives, we refer to the respective websites. Given the prior experience of the research team, and more importantly, the flexibility of VISSIM, we opted to use this microsimulation package in this project.

3.1.2 Mesoscopic Modeling Techniques

Route choice models predict the paths that users will follow when traveling in a transportation network. Classically, route choice forms the fourth and final step of the transportation planning process, once travel demand is known and the choice of mode has already been made. The most common assumption is that all users choose the route that minimizes their travel time; this allows routes to be found using efficient network algorithms such as those developed by Dijkstra [31], Dial [32], Loui [33], Ziliaskopoulos and Mahmassani [34], or Waller and Ziliaskopoulos [35]. The state-of-the-art in this domain can identify the routes chosen by travelers in the presence of time-varying and uncertain costs, both of which are critical for accurately modeling real-world transportation networks.

Because all users are simultaneously trying to minimize the travel times they will each experience, the resulting state is an equilibrium in which nobody can reduce their travel time by switching routes. This condition was first identified by Wardrop [36] and Beckmann et al. [37]. The traditional solution procedure is based on Frank and Wolfe [38], although faster and more accurate methods have been developed by Jayakrishnan et al. [39], Bar-Gera [40], and Dial [41]. Adaptations have also been made to account for user error in perceiving travel times, leading to a class of stochastic user equilibrium models (first developed by [42]); some limited demand elasticity effects (first found in [37]); and multiclass equilibrium models where different types of users (for instance, transit, HOVs, and single-occupant vehicles) see different travel times [43].

These traffic assignment models have sound mathematical properties that allow solutions to be found efficiently; however, a major shortcoming is their inability to account for how traffic evolves over time. This is critical when considering dynamic traffic management strategies that require the explicit modeling of time. Moreover, traffic itself is inherently dynamic, consisting of congestion that evolves over time, and queues that form and dissipate at traffic signals. Thus, by explicitly modeling changing network conditions, dynamic modeling can represent traffic flow in a far more accurate manner. These needs have been addressed with the creation of dynamic traffic assignment (DTA) models, which can account for these factors. The first DTA model was developed by Merchant and Nemhauser [44], and a thorough overview of progress since then is available in Peeta and Ziliaskopoulos [45].

Unlike the models mentioned in the previous section, there is no standard DTA model. Currently, the most promising approaches are based on traffic simulation models, as these are able to capture the most realism in how traffic evolves over time. Examples of simulation-based

DTA software include DynaMIT [46], VISTA [47], DYNASMART [48], and DynaCHINA [49]. These often use efficient traffic propagation procedures such as the cell transmission model [50].

Given the prior experience of the research team, we employed VISTA as the mesoscopic traffic simulator in the current project.

3.1.3 Multi-Resolution Simulation

From the previous sections, it is clear that both microscopic as well as mesoscopic simulation have their advantages and disadvantages: the former is far more accurate when properly calibrated (but computationally challenging), whereas the latter is less detailed but computationally feasible. Hence it is natural to consider so-called hybrid models, combining the advantages of the two modeling paradigms. This multi-resolution approach is particularly appropriate when considering dynamic traffic management strategies like speed harmonization and peak-period shoulder use: these strategies tend to be employed locally (microsimulation can yield accurate traffic patterns in these local areas), while the consequences of such measures can be—potentially—felt at a much larger scale (mesoscopic simulation can yield sufficiently accurate traffic patterns in the entire network within a reasonable computational time). In particular, microsimulation is able to capture the impacts of the dynamic traffic management strategies on driving behavior such as lane-changing and weaving. On the other hand, mesoscopic simulation is able to accurately model the change in route choice and temporal congestion patterns at the network level (Figure 3.1).

Before we present a detailed discussion of how the multi-resolution framework can be implemented, we will first discuss several performance measures that can be used to evaluate the impacts of both speed harmonization as well as peak-period shoulder use.

Figure 3.1: Multi-resolution modeling approach

3.2 Performance Measures

An objective evaluation of the effectiveness of dynamic management strategies is at least as important as the implementation itself: without an objective evaluation, it is simply not known whether the newly introduced strategies are effective at all. Moreover, oftentimes, it is necessary to justify the commitment of huge amounts of financial resources to new projects. In order to perform an objective evaluation of speed harmonization and peak-period shoulder use, we need performance measures. In this section we present and discuss various performance measures that are able to capture the effectiveness of the dynamic traffic management strategies considered in this project. In the discussion, we distinguish local and network-wide performance measures. Local performance measures are designed to capture the local impacts, i.e., the impacts on the test corridor itself (and its direct surroundings). When local measures indicate an improvement in the local traffic conditions, it is not necessarily true that the network-level impact is positive as well. In fact, one can imagine situations in which bottlenecks shift to other parts of the network, resulting in a, perhaps, worse overall, system-wide condition. Network-level performance measures are designed to capture these global impacts.

In the following discussion, we will discuss both local and global measures of performance. The change in a certain performance measure is computed based on the conditions before and after implementation of speed harmonization and/or peak-period shoulder use.

3.2.1 Local Performance Measures

Relative change in average speed

Speed harmonization lowers the speed limit temporarily in order to create conditions for a “smoother” flow of traffic. Hence, one might hypothesize that speed harmonization can potentially lower the average speed on the test corridor. On the other hand, one might argue that because of the more uniform traffic flow, it is conceivable that the average speed among all road users on the test corridor increases. With peak-period shoulder use, an additional running lane is provided. It is to be expected that the average speed is to be increased if the number of vehicles traveling on the test corridor remains the same. In general, for both dynamic traffic management strategies, a positive change in the average speed is desired.

Relative change in average density

The average density of a road section is defined as the number of vehicles per unit length of the road. Everything else being equal, a low average density is preferred as this is beneficial for the safety of road users. Hence in terms of the relative change in average density, it is desirable to see a change that is large in magnitude and negative in sign.

Relative change in average throughput across a section

The average throughput across a given section is defined as the average number of vehicles passing a given section within a given amount of time. Obviously, everything else being the same, a larger throughput is preferable.

3.2.2 Network-wide Performance Measures

Relative change in total trip time between a given origin-destination pair

For both speed harmonization and peak-period shoulder use one can anticipate that drivers change their routes as a result of the new driving conditions. Travel times between certain locations might increase because of the increased travel demand on certain roads (for example, some people might avoid roads that are subject to speed harmonization and take a detour). On the other end, it is also conceivable that travel times between other origin-destination (OD) pairs decrease because of the traffic management strategies. Ideally, one would like to see large negative changes (i.e., shorter travel times) in the trip time between any given OD pair.

Relative change in total system-wide travel time

The previous performance measure considers the relative change in travel time for all OD pairs individually. As a decision maker, it is often not possible to examine the individual changes. Rather, one performance measure for the entire network is desired. Such performance measure is provided by the change in total system travel time, which is defined as the sum of the changes in the individual OD pairs.

3.3 Implementation in VISSIM/VISTA

The starting point of the multi-resolution approach is a simulation model of the Austin area in the mesoscopic traffic simulator VISTA. In order to illustrate the DTMs investigated in this project using a real-world example, we selected the stretch of MoPac (Loop 1) in Austin between Enfield Road and 45th Street (see Figure 3.2) for demonstration purposes. This corridor is known for its recurring congestion. Moreover, for this stretch of Loop 1 we have sufficient data for calibration and we possess a calibrated mesoscopic simulation model to assess the network impacts.

The first step in the approach is to perform traffic simulation in VISTA for the “entire” Austin network (engineering judgment is needed here to determine what constitutes the “entire” network, i.e., the parts of the network where the effects of the DTM strategies are likely to be felt). Based on this simulation run, performance measures about the current (i.e., pre-speed harmonization and peak period shoulder use) network are collected. Furthermore, the vehicular flows at the boundaries of the Loop 1 area under study are also extracted from the simulation results. These boundary conditions are then fed into the VISSIM network of Loop 1 that we have built for this project. Microsimulation is performed to determine the current, pre-speed harmonization/ pre-peak period shoulder use traffic conditions on Loop 1. The next step is to apply some form of speed harmonization/peak-period shoulder use (i.e., using some specific control strategy). Because of the modified speed limits and/ or roadway geometrics, it is to be expected that people change their driving behavior, routes, and so on. In order to determine the local impact of the particular speed harmonization/peak-period shoulder use strategy, we again perform microsimulation in VISSIM, after the implementation of speed harmonization/peak period shoulder use. New performance measures are collected for the post-speed harmonization/post-peak period shoulder use conditions. A comparison between these pre- and post- speed harmonization/peak period shoulder use conditions will reveal the local impact of speed harmonization/peak period shoulder use. In order to evaluate the network-wide impact of speed harmonization/peak period shoulder use, the post-speed harmonization/post-peak period shoulder use measures on Loop 1 have to be represented in VISTA’s Austin network. To this end, we will perform a systematic procedure in which parameters in VISTA’s Austin model (e.g., cell capacities) are changed to reflect the change in traffic conditions on Loop 1. That is, parameters in the VISTA network will be changed so that the traffic patterns, post-speed harmonization/post-peak period shoulder use, observed on Loop 1 are approximately the same in both the VISSIM as well as the VISTA network. For instance, in case of peak-period shoulder use, one can temporarily increase cell capacities in VISTA to represent the addition of a shoulder lane as a running lane. Once these settings have been found, we perform a new run of mesoscopic simulation (with the new, post-speed harmonization settings/post-peak period shoulder use settings). Based on the simulation results, performance measures can be calculated and compared with the (network-wide) pre-speed harmonization/pre-peak period shoulder use measures. This comparison will yield the network-wide impacts of speed harmonization/peak period shoulder use. Figure 3.3 provides a pictorial summary of this discussion.

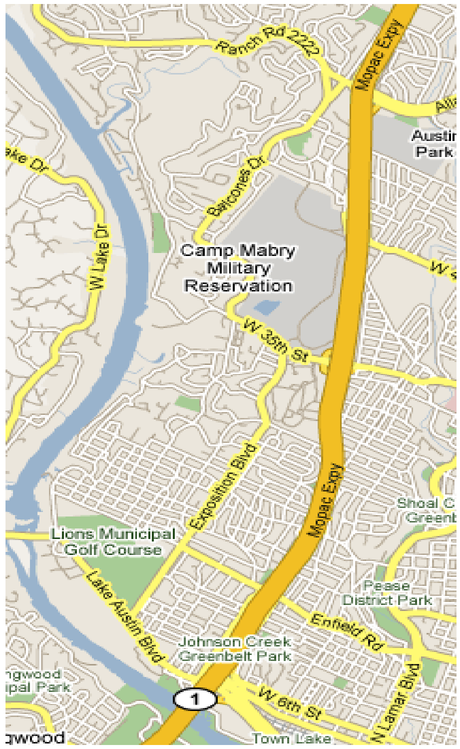


Figure 3.2: Test corridor for speed harmonization and peak-period shoulder use (Loop 1 in Austin, TX)

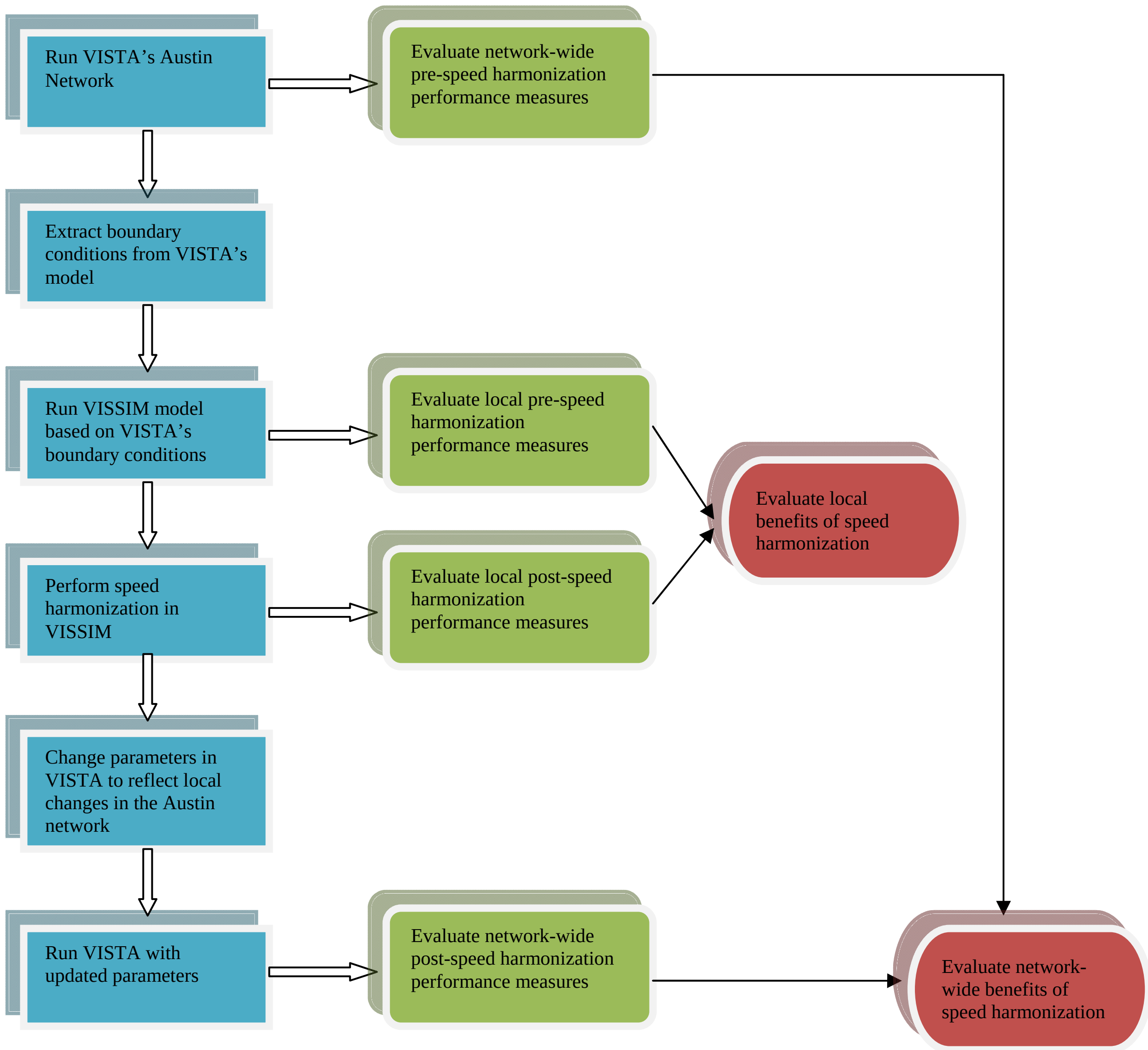


Figure 3.3: A multi-resolution approach to evaluate the impacts of speed harmonization and peak-period shoulder use

Chapter 4. Control Strategies Speed Harmonization

One of the most important determinants of the success of speed harmonization is the control strategy. That is, the control algorithm that determines when and how the speed limit is to be adjusted on a given road segment. These control algorithms can be subdivided into two groups. The first group concerns the class of online control strategies: optimal speed limits are dynamically determined over time, based on the prevailing traffic conditions. The second group consists of offline control algorithms. In this latter class of algorithms, the optimal speed setting is determined based on historical information. Ideally, one would prefer online control algorithms as these are based on prevailing traffic conditions. However, as speed harmonization requires a dense deployment of ITS infrastructure, the provision of sufficiently large amounts of real-time information might not be available in certain parts of a road network. In such cases, it becomes necessary to consider offline algorithms.

The remainder of this chapter is organized as follows. In Section 4.1 we provide some theoretical basis of traffic flow theory that is needed for the understanding of the proposed algorithms. Section 4.2 presents an offline algorithm. Numerical results are provided to illustrate its effectiveness. An online control strategy is then examined in Section 4.3, followed by numerical results.

4.1 Some Traffic Flow Theory

In this section we review the fundamentals of traffic flow theory because the algorithms proposed in the next sections depend heavily on this theory. For a more comprehensive treatment of the subject, we refer the reader to May [51].

The fundamental variables of interest in traffic flow theory are flow (q), density (k), and speed (u). The flow q is defined as the number of vehicles passing through a certain point of a road segment. The unit of measurement of flow is vehicle per hour (vph). Note that the measurement of flow is often performed over a shorter time period, but the result is converted to an hourly equivalent. The density k has a unit of vehicles per mile (vpm) and measures the number of vehicles on a section of a road segment. Two speeds can be distinguished in the traffic flow literature. The first is time mean speed $\bar{u}_t$, which is mathematically defined as

$$\bar{u}_t = \frac{1}{n}\sum_{i=1}^{n} u_i$$

where u_i denotes the speed of vehicle i passing a fixed point on a road segment. The second is the space-mean speed and is defined as the harmonic mean of u_i:

$$\bar{u}_s = \frac{n}{\sum_{i=1}^{n} 1/u_i} = \frac{nL}{\sum_{i=1}^{n} t_i}$$

where t_i and L denote the time it takes for vehicle i to traverse the road segment and the length of the segment, respectively.

Of course, the fundamental variables are related. More precisely, they are related via the following flow-density relation:

$$q = k \cdot \bar{u}_s(k) \quad (1)$$

where we have emphasized that the space-mean speed is dependent on the density k. Two of the more popular choices for the functional relationship $\bar{u}_s(k)$ is given by Greenshield and Greenberg (e.g., see [52]). Here we adopt Greenshield's model, which postulates a linear relationship between the space-mean speed and the density:

$$\bar{u}_s(k) = u_f - \frac{u_f}{k_j} k \quad (2)$$

where u_f and k_j denote the free flow speed and jam density, respectively. Substituting (2) in (1) reveals a quadratic relationship between density and flow:

$$q = k\left(u_f - \frac{u_f}{k_j} k\right) \quad (3)$$

Figure 4.1 depicts the instance of equation (3) when u_f = 60 mph and k_j =115 vpm.

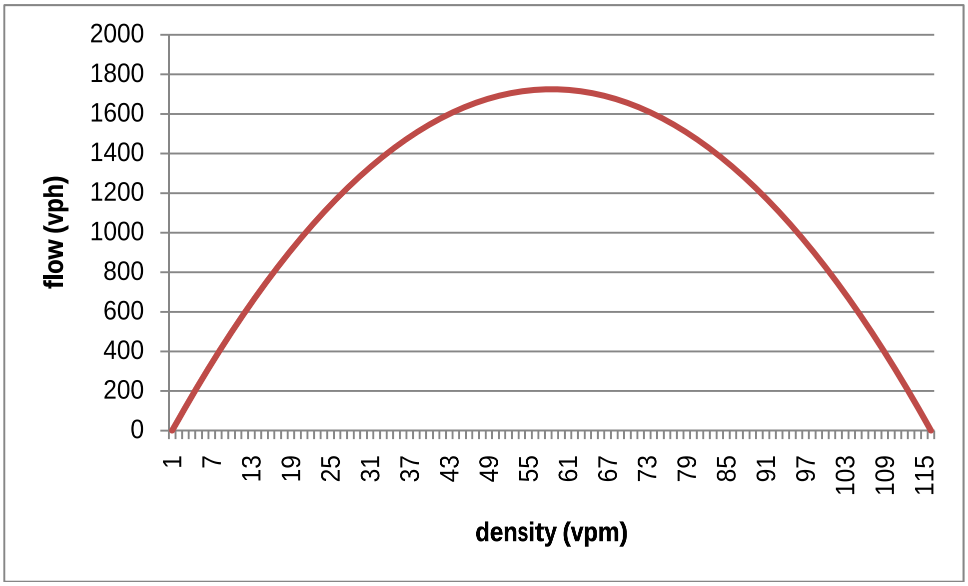


Figure 4.1: Flow density relation based on Greenshield's model

Empirical flow-density curves can be constructed using detector data. They can be used to calibrate equations (2) and (3). Figure 4.2 shows an empirical flow-density curve for a section of IH 880S in California (adopted from [53]).

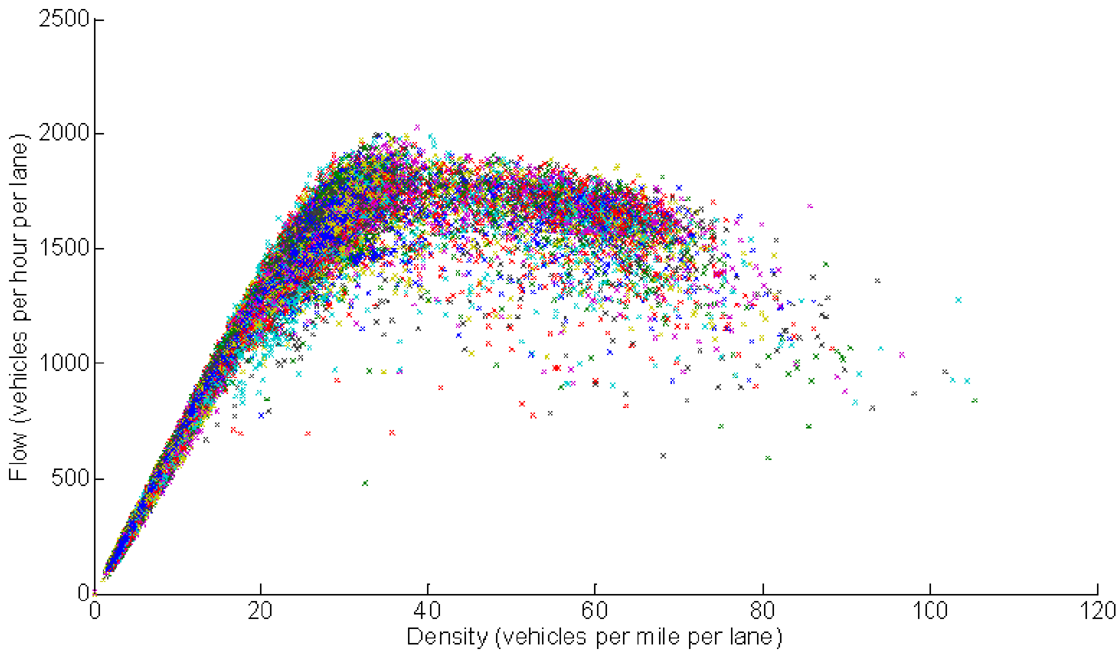


Figure 4.2: Flow-density diagram for a section of IH 880S. Source: Dervisoglu et al. [53]

By expressing the density in terms of the space-mean speed using (2) and substituting the resulting expression in (1) yields the following quadratic relationship between space-mean speed and flow:

$$q = \frac{k_j}{u_f}\left(u_f - \bar{u}_s\right)\bar{u}_s \tag{4}$$

Figure 4.3 depicts relation (4) for the case when u_f = 60 mph and k_j =115 vpm.

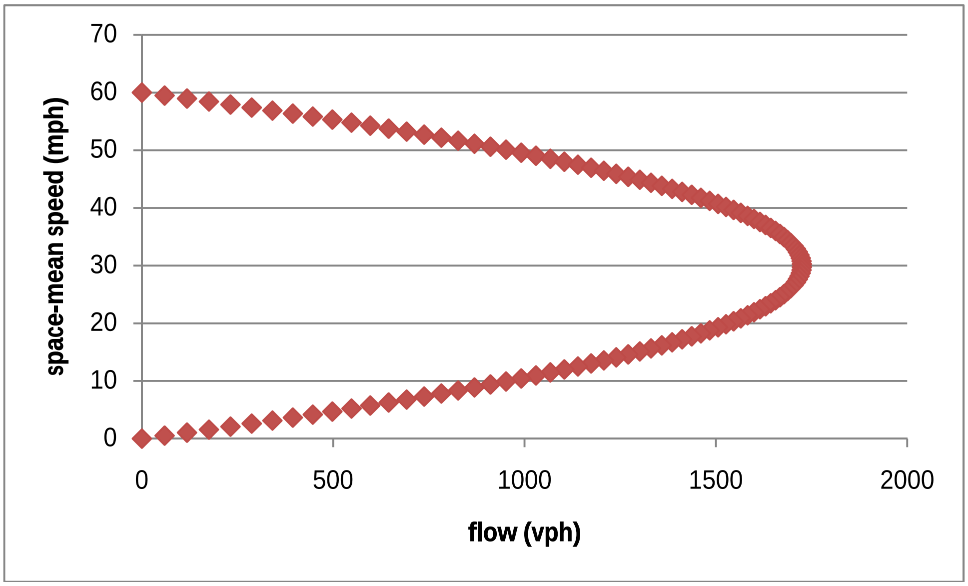


Figure 4.3: Space-mean speed—flow relation based on Greenshield's model

As can be seen from Figure 4.3, there are two values of the space-mean speed that are associated with each flow value. The higher value corresponds to the uncongested situation and the lower value corresponds to the congested situation. Also, note that the rightmost point on the curve represents the maximum flow (i.e., the capacity) of the road under consideration. In this case, it can be seen to be approximately 1,700 vph.

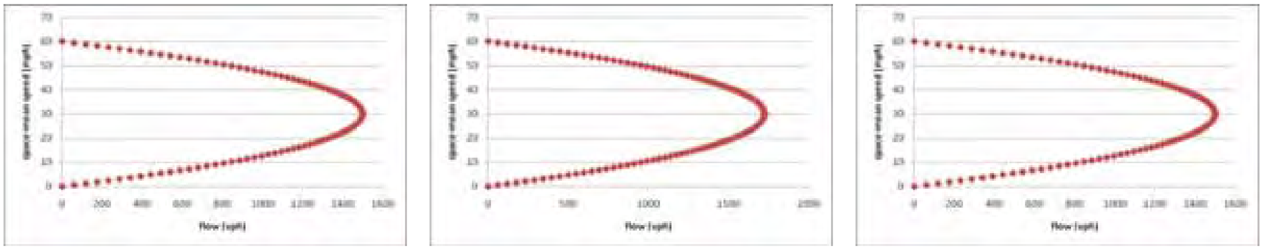
4.2 An Offline Algorithm for Variable Speed Limits

The validity of offline algorithms depends heavily on the assumption that historical traffic patterns repeat over time (i.e., daily). With such an assumption, we can associate a traffic flow q_t with time t of the day for a particular location. For example, based on historical data, we might know that the flow on a particular day (Monday, for example) and location during the morning peak-hour is (on average) 1,700 vph. An offline algorithm then automatically assumes that the flow *on every Monday morning peak-hour* at the same location is also 1700 vph (until new measurements suggest that the value has to be adjusted), based on which it will select appropriate speed limits (rather than using prevailing traffic conditions).

To illustrate the proposed offline algorithm, consider the freeway in Figure 4.4, which consists of three segments. Suppose that we have calibrated three $(\overline{u}_s, q)$-curves (cf. Figure 4.3) for this particular road segment on a Monday morning and that Figure 4.3 represents the $(\overline{u}_s, q)$ diagram for road segment 3. Furthermore, suppose that the flow on segment 3 of the road is known to be equal to 1600 vph (based on historical observations) at 8:00 a.m. in the morning (note that its capacity is approximately equal to 1700vph; see Figure 4.3). As the flow on segment 3 nearly equals its capacity, one can imagine that it is judicial to reduce the number of arriving vehicles at this segment to prevent the onset of congestion, i.e., to prevent that flow reaches capacity. To this end, we perform speed harmonization for the upstream segments (segments 1 and 2). In Figure 4.5 we have shown the $(\overline{u}_s, q)$-diagram for segment 2. Suppose that the current flow (i.e., Monday morning, 8:00 a.m.) at segment 2 is estimated to be 1,700 vph (at an average speed of about 40 mph); see Figure 4.5. In order to prevent the flow in segment 3 reaching its capacity (for example, due to random minor incidents etc.), we thus have to choose a speed limit at segment 2 such that

$$q(2) < c(3) = 1700 \tag{5}$$

where $q(2)$ and $c(3)$ denote the flow at segment 2 (that will enter segment 3) and the capacity of segment 3, respectively. From Figure 4.5, it is clear that a range of speeds exists that satisfies criterion (5). In particular, all speeds below (about) 22 mph would suffice. Hence it is natural to choose the maximum speed such that (5) is satisfied, which in this case equals 22 mph (or some other rounded value, e.g., 20 mph). In Figure 4.5 we have shown with an arrow how the flow on segment 2 changes when the new speed limit is set to 20 mph (i.e., the flow on segment 2 reduces to 1,600 vph). Of course, depending on the flow on segment 1, the new speed limit on segment 1 might need to be reduced as well in order to prevent segment 2 from becoming a bottleneck. After the peak-period, the speed limit can be increased again to its original value. This offline algorithm is summarized in Section 4.2.1, in which we assume that we have n roadway segments.



Segment 1 **Segment 2** **Segment 3**

Figure 4.4: Example freeway consisting of 3 segments, each having its own space-mean speed—flow diagram. Traffic flow is from left to right.

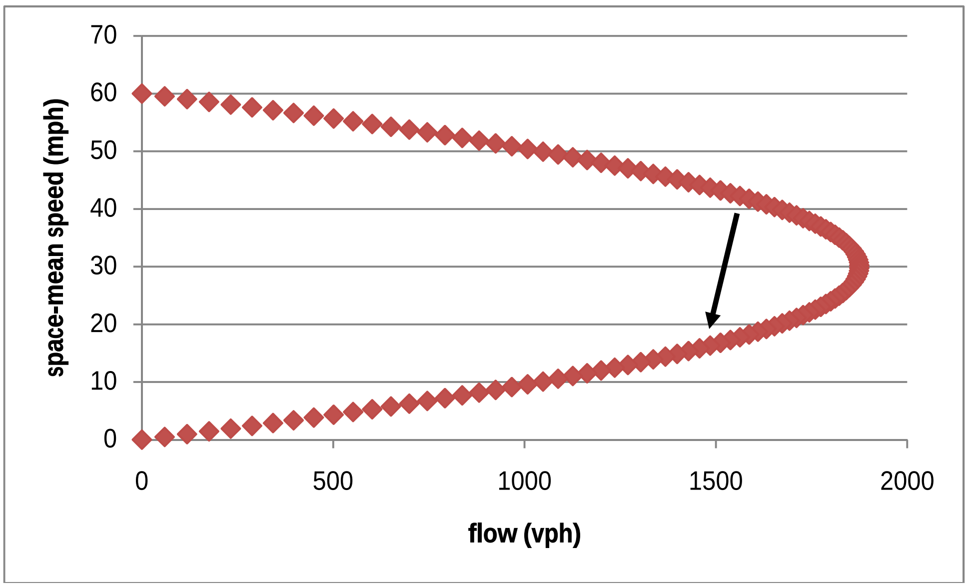


Figure 4.5: Space-mean speed—flow curve for segment 2

4.2.1 Offline Algorithm Speed Harmonization

Input $(\bar{u}_s, q)$-curves for each of the *n* road segments for time *t* of the day

Output "Speed-harmonized road segments" for time *t* of the day

Step 1. Pick the most downstream road segment *k* for which the flow almost reaches capacity.

Step 2. FOR all road segments *r* = *k*-1, *k*-2,…, 1

DO select a speed for segment *r* such that $q(r) < c(r+1)$

set $c(r) \leftarrow q(r)$

END

END

Step 3. When flow reduces to normal, off-peak values, reinstall original speed limits.

Notes:

- In Step 1 we have, without loss of generality, implicitly assumed that we can find a road segment that is operating near capacity, as speed harmonization is not needed in case such a segment does not exist. Note that in an offline framework, these bottleneck segments are assumed to be known.
- The speed selection in Step 2 can be accomplished in various ways, both subjectively (e.g., based on engineering judgment) as well as objectively (e.g., via simulation). We prefer the latter method. In the numerical case study that follows we use microsimulation to select "optimal" speed limits.
- In general, speed harmonization is needed only during peak hours. Because the presented algorithm is an offline procedure, the algorithm assumes it is known at what time Step 3 of the algorithm is executed, i.e., at what time the speed limits are restored to their original values.

As a final remark, because of the offline character of the control algorithm, the setting of speed limits does not account for important real-time factors, such as weather-related conditions (e.g., visibility) and pavement conditions (e.g., dry/wet). Hence it remains important that—before any of the offline speed limits are posted on variable message signs—a check is performed by an operator to prevent dangerous situations. On the other hand, if only speed limit reductions are considered (as is the case in all instances of speed harmonization encountered in the current literature), the posted speed limit will always be lower or equal to the static speed limit. Thus, as long as the public is aware that the posted speed limits are maximum values (rather than recommended), it is always an improvement on the existing static speed limit.

4.2.2 Numerical Case Study

To test the control strategy proposed in the previous section, we developed two microsimulation models of the test corridor on Mopac (the 2.5 mile section between Enfield Rd. and West 45th Street, northbound); see Figure 4.6. We treat this study section as one segment for the purpose of offline VSL implementation, and any change in recommended speed limit applies to the whole section. Therefore, this case study can be considered a specific implementation of the general offline VSL algorithm presented earlier.

There are two different simulation models developed for this study: one peak-period simulation model is developed for congestion scenario, while the other is for the uncongested case. To calibrate the peak-period model, we used 15-minute aggregates detector data from 2007 (Table 4.1). Uncongested model was developed by uniformly reducing the mainline and ramp volumes in the peak-period model by 30%. The uncongested model is used to qualitatively study the impact of offline VSL when this strategy is implemented before the onset of congestion.

Table 4.1: Snapshot of loop detector data

STN_ID	LANE_QTY	STA_TIME	VOLUME	FLOWRATE	OCC	SPEED	TRUCKS	SPD_DAYS	VOL_DAYS	OCC_DAYS	TRK_DAYS	Year
164	2	0:00	99.989	199.98	0.94	61	1.2811	185	185	185	185	2007
164	2	0:15	85.622	171.24	0.76	61	1.4162	185	185	185	185	2007
164	2	0:30	72.822	145.64	0.62	61	1.1676	185	185	185	185	2007
164	2	0:45	61.848	123.7	0.49	61	1.0217	184	184	184	184	2007
164	2	1:00	53.005	106.01	0.4	61	1.1749	183	183	183	183	2007
164	2	1:15	44.978	89.956	0.31	61	1.0608	181	181	181	181	2007
164	2	1:30	39.783	79.567	0.26	61	1.3556	180	180	180	180	2007
164	2	1:45	36.654	73.307	0.24	61	1.4749	179	179	179	179	2007
164	2	2:00	32.514	65.028	0.22	61	1.3503	177	177	177	177	2007
164	2	2:15	32.282	64.565	0.2	61	1.2768	177	177	177	177	2007

Figure 4.6: VISSIM model test corridor Loop 1

Loop detector data was available at three locations (9 ½ Street, Westover Road, and 45th Street) for the chosen section of Loop 1. This data was used to calculate average hourly volume and speed at these location for evening peak period 3:00 p.m.–7:00 p.m. Traffic density and level of service (LOS) were calculated for the study section, and are shown in Table 4.2. From these data we can see that the corridor is highly congested during the peak hours.

Table 4.2: Level of service (LOS) for evening peak period

	Density (veh/mi/ln)			Level of Service (LOS)		
Time	9 1/2 St	Westover Rd	45th St	9 1/2 St	Westover Rd	45th St
3 PM - 4 PM	33	36	33	D	E	D
4 PM - 5 PM	47	57	44	F	F	E
5 PM - 6 PM	52	61	50	F	F	F
6 PM - 7 PM	34	43	37	D	E	E

A microsimulation model of Mopac for the evening peak hours 4:00 p.m.–6:00 p.m. was developed in VISSIM and was calibrated using available loop detector data. A guideline provided by the FHWA for the calibration of simulation models uses the Geoffrey E. Havers (GEH) formula, which is defined as:

$$GEH = \sqrt{\frac{2(Observed - Simulated)^2}{(Observed + Simulated)}}$$

where Observed and Simulated denote the observed and simulated volumes respectively.

More precisely, the FHWA recommends a GEH value of less than 5 at 85% of the locations, which is clearly satisfied by our calibrated model (Table 4.3). In addition to the GEH statistic, absolute percent difference between the observed and calibrated volume was calculated. Percent difference was less than 5% for most of the location and time interval, and indicated to the high fidelity of the calibration model.

Table 4.3: Calibration results for the microsimulation model

Detectors on MoPac NB	Time	Observed Volume (veh/hr)	Simulated Volume (veh/hr)	% Difference	GEH
9 1/2 St	4 PM - 5 PM	2448	2515	2.7	1.3
Westover Rd	4 PM - 5 PM	4605	4322	-6.1	4.2
45th St	4 PM - 5 PM	5176	5199	0.4	0.3
9 1/2 St	5 PM - 6 PM	1826	1767	-3.2	1.4
Westover Rd	5 PM - 6 PM	3717	3897	4.8	2.9
45th St	5 PM - 6 PM	4702	4742	0.9	0.6

Offline implementation of variable speed limits (VSL) was done by dividing the study period into four half-hour periods (4:00–4:30 p.m., 4:30–5:00 p.m., 5:00–5:30 p.m., and 5:30–6:00 p.m.) and then applying different speed limits to determine their impact on traffic operations and safety condition. The posted speed limit of the freeway is 65 mph. These different speed limits were tested for the offline VSL: 60 mph, 55 mph, 50 mph, and 45 mph. This resulted in 16 combinations (4 half-hour periods x 4 speed limits) of offline VSL scenarios. The results obtained from these scenarios were aggregated by speed limits and time of implementation; important results are highlighted next.

- Speed harmonization resulted in a small increase in throughput under congested situations (Table 4.4).

Table 4.4: Effect of offline VSL on throughput (peak-period model)

Variable Speed Limit (mph)	Throughput (% change)	
	Westover Rd	W 40th St
Base Case (65 mph)	-	-
60 mph	1.3	0.9
55 mph	1.4	1.0
50 mph	1.6	1.2
45 mph	1.0	0.6

- Speed harmonization has negligible effect throughput for then the uncongested model (Table 4.5).

Table 4.5: Effect of offline VSL on throughput (uncongested model)

Variable Speed Limit (mph)	Throughput (% change)	
	Westover Rd	W 40th St
Base Case (65 mph)	-	-
60 mph	0.0	0.0
55 mph	0.0	-0.1
50 mph	0.0	-0.1
45 mph	-0.1	-0.1

- Speed harmonization decreased delay for both the congested and uncongested model (Tables 4.6 and 4.7). (Delay is calculated as the difference between the actual travel time and posted speed limit travel time. So, delay for the VSL scenarios are calculated with respect to the new speed limit, and not the static speed limit of 65 mph, for the duration of VSL implementation).

Table 4.6: Effect of offline VSL on delay (peak-period model)

Variable Speed Limit (mph)	Total Delay per Vehicle (% change)	Stopped Delay per Vehicle (% change)
Base Case (65 mph)	-	-
60 mph	-3.8	-2.3
55 mph	-3.6	-1.4
50 mph	-7.0	-3.3
45 mph	-7.1	-1.9

Table 4.7: Effect of offline VSL on delay (uncongested model)

Variable Speed Limit (mph)	Total Delay per Vehicle (% change)	Stopped Delay per Vehicle (% change)
Base Case (65 mph)	-	-
60 mph	-8.9	-18.5
55 mph	-12.0	-16.7
50 mph	-17.8	-24.6
45 mph	-18.0	-22.2

- Speed harmonization decreased delay more if implemented early on (Table 4.8).

Table 4.8: Offline VSL effect on delay by time of implementation

Variable Speed Limit Hours	Total Delay per Vehicle (% change)	
	Peak-period Model	Uncongested Model
No VSL	-	-
4:00-4:30 PM	-5.7	-16.9
4:30-5:00 PM	-6.8	-20.5
5:00-5:30 PM	-5.4	-8.9
5:30-6:00 PM	-3.6	-10.4

- Speed harmonization reduces the number of lane changes (Table 4.9).

Table 4.9: Effect of offline VSL on lane changes

Variable Speed Limit (mph)	Peak-period Model		Uncongested Model	
	Number of Lane Changes	% Change	Number of Lane Changes	% Change
Base Case (65 mph)	68444	-	31388	-
60 mph	68312	-0.19	31411	0.07
55 mph	67297	-1.68	31045	-1.09
50 mph	67288	-1.69	30689	-2.23
45 mph	66245	-3.21	30474	-2.91

- Speed harmonization reduces the number of stops in traffic (Table 4.10).

Table 4.10: Effect of offline VSL on number of stops

Variable Speed Limit (mph)	Number of Stops per Vehicle (% change)	
	Peak-period Model	Uncongested Model
Base Case (65 mph)	-	-
60 mph	-4.3	-8.3
55 mph	-2.7	-8.9
50 mph	-4.2	-14.0
45 mph	-3.8	-11.0

- Speed harmonization may have *adverse* impact on speed variability *if applied late* (Table 4.11).

Table 4.11: Effect of offline VSL on speed variability (peak-period model)

Variable Speed Limit (mph)	Speed Variability (% change)	
	Westover Rd	W 40th St
Base Case (65 mph)	-	-
60 mph	1.6	4.4
55 mph	2.5	3.2
50 mph	0.3	1.2
45 mph	1.2	-1.8

- Speed harmonization reduces the speed variability when applied before the onset of congestion (Table 4.12).

Table 4.12: Effect of offline VSL on speed variability (uncongested model)

Variable Speed Limit (mph)	Speed Variability (% change)	
	Westover Rd	W 40th St
Base Case (65 mph)	-	-
60 mph	-3.1	-4.0
55 mph	-5.3	-6.5
50 mph	-6.0	-8.5
45 mph	-5.0	-10.0

4.3 An Online Algorithm for Variable Speed Limits

The use of online control algorithms is much more common than its offline counterpart. This results in a large body of literature on online control. For completeness, we first present a representative sample of the literature on online control strategies.

4.3.1 Literature Review

Online control algorithms are characterized by the use of real-time traffic and environmental data to determine optimal speed limits. In the literature, numerous algorithms ranging from simple and easily implementable to advanced and rather fancy rules have been proposed [54]. In the following we only provide a small, but representative, sample to illustrate the typical features of these algorithms.

Washington State and Finland use simple matrices (that are dependent on traffic conditions) to select advisory speeds. In the Netherlands, a two-step algorithm is implemented [13]. In the first stage, a decision on whether speed limit intervention is necessary is made by comparing the one-minute traffic flow volumes with upper and lower boundary values. If speed limit intervention is deemed to be necessary on a section, the new speed limits (typically between 70 and 90 km/h, or 43 and 56 mph) are chosen out of a finite set, after comparing the average of the mean speed of the signal stations of a section with several boundary values. Nevada uses a logic tree to deduce the optimal speed limit from current traffic conditions (using variables such as speed, visibility, and pavement conditions). In the United Kingdom, the speed limit reduces from 70 mph to 60 mph when volume exceeds 1,650 veh/hour/lane. It reduces to 50 mph when the volume exceeds 2050 veh/hour/lane.

More advanced and fancy algorithms have been developed in other instances, for example, based on fuzzy logic [55]. In Lee et al. [56], a procedure is proposed to dynamically determine the time at which speed limits are to be reduced, i.e., when speed harmonization is to be applied. They use a regression model predicting the expected number of crashes (they called it crash potential) based on factors such as speed differentials and difference in volumes across lanes. When the crash potential is above a certain threshold, the speed limit is reduced to some value in a pre-specified finite set of speed limits. Using microscopic simulation, they found that optimal intervention durations (i.e., the length of the time intervals in which the speed limit is constant should not be too short. They recommended a value between 5 to 10 minutes). It was found that variable speed limits are beneficial for the crash potential. A similar study was conducted in Abdel-Aty [57]. Hegyi et al. [58] conducted a theoretical study to use speed harmonization to minimize or eliminate shock waves induced by congestion. The model proposed by these authors searched for speed limits resulting in minimum total travel time, subject to a safety constraint preventing speed changes of more than 10km/h at a time. Advanced control theory was used.

What is remarkable about the above sample of theoretical research and real world case studies is that they all report benefits, either for congestion reduction or safety (or both). Of course, different works report numerically different benefits (we believe that this is purely a consequence of different model assumptions or driver characteristics, rather than the superiority of one of the algorithms). Hence this leads us to the conjecture that there does not seem to be significant differences in the proposed control algorithms currently available in the literature. In light of this observation, we suggest the use of simple online control algorithms. Except for the fact that similar (compared to fancy algorithms) beneficiary results have been reported in the literature, these algorithms are simple to implement and, perhaps more importantly, much more transparent to the operators at traffic management centers.

As we have noted, we believe that simple online control algorithms can potentially be as effective as more involved algorithms. Moreover, the majority of *real-life and successful* instances of speed harmonization (as opposed to simulation exercises) employ these relatively simple strategies (e.g., in the United Kingdom). Motivated by these examples, we suggest using a modified version of the control strategy used by Allaby et al. [57] for Queen Elizabeth Way near Toronto, Canada. This algorithm is presented in Figure 4.1.

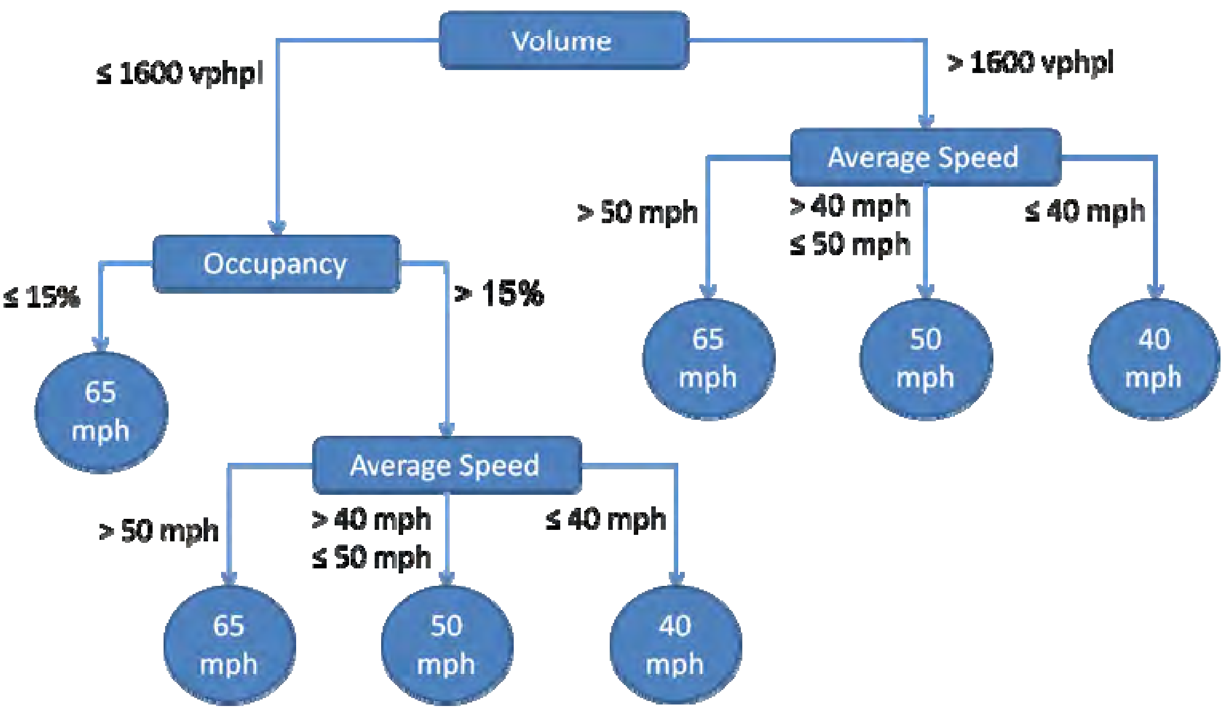


Figure 4.7: Online VSL algorithm. Source: Allaby et al. [59]

Real-time data can now be used to determine the start of modified speed limits. Moreover, due to real-time information, the speed limit can now be easily modified (i.e., increased and decreased) multiple times during the peak-hour period. Of course, this frequency should not be too high in order to prevent "erratically" changing speed limits [59]. The basic idea of the algorithm is to examine each bottleneck (starting from the most downstream, and working backwards) and determine the associated optimal speeds upstream of it. Again, in this particular study only one segment is considered. A general framework for online VSL implementation is presented here.

4.3.2 Online Algorithm Speed Harmonization

Input

- $(\bar{u}_s, q)$-curves for each of the *n* road segments. Note that we can extract the maximum capacities $c_0(k)$, $k = 1, 2, .., n$ of the road segments from these curves.
- Current speed limits $s_0(k)$, $k = 1, 2, .., n$ of the road segments.
- The minimum intervention duration T_{min} , *i.e.*, the minimum time interval in which the speed limit remains constant.

Output
A set of dynamically changing speed limits for each of the road segments.

INITIALIZATION $c(k) \leftarrow c_0(k)$, $s(k) \leftarrow s_0(k)$

FOR $k = n, n\text{-}1, .., 2$
    IF $q(k) \approx c_0(k)$
        FOR all road segments $r = k\text{-}1, k\text{-}2, \ldots, 1$
            DO select a speed $u(r)$ for segment *r* using the online VSL algorithm.

            END DO
        END FOR
    END IF
    set $c(r) \leftarrow c_0(r)$
END FOR
Display new speed limit vector $s(r)$
Wait for T_{min} time units, set $s(r) \leftarrow s_0(r)$ and repeat the algorithm.

Online VSL algorithm is implemented in the VISSIM microsimulation model using VISSIM's vehicle actuated programming (VAP) module. An implementation code was written in VAP (see Appendix A), which checked traffic conditions every 5 minutes and selected a speed limit using the algorithm presented here.

Remarks:

- Different values of T_{min} are reported in the literature (e.g., Lee et al. [56] suggest a value between 5 to 10 minutes; Abdel-Aty et al [57] recommends a value of 10 minutes). We adopted T_{min} = 5 min for our purposes.

- Note that when for a given iteration of the algorithm no segment satisfies the condition $q(k) \approx c_0(k)$, then the speed limit will be returned to its original value.
- As in the offline algorithm, the speed selection can be accomplished in various ways, both subjectively (e.g., based on engineering judgment) as well as objectively using the fundamental diagrams. We prefer the latter method and adopted an algorithm such as presented in Figure 4.1.
- Note that in a given iteration, $s(k)$ is a non-increasing sequence. That is, once the speed limit of a given section has been lowered, the algorithm ensures that (in the same iteration) subsequent speed limit modifications are such that the speed limit can only be further reduced on the section in question. This prevents that the lowering of speed limits in support of downstream bottleneck i are cancelled when we consider bottleneck i-m, where $0 < m < i$.
- If we made the additional assumption that visibility information and pavement conditions are known, we can also incorporate this information into the proposed algorithm by imposing rules on the speed selection procedure (e.g., "if visibility is less than x feet, then set speed limit equal to y mph").

4.3.3 Numerical Case Study

To test the effectiveness of variable speed limits and peak-period shoulder use, three different models were developed. These models simulated the following scenarios: base case, variable speed limits implementation, and simultaneous implementation of variable speed limits and shoulder use. These scenarios were compared with the base case (when neither of the two traffic management strategies are implemented) and traffic operations and safety benefits obtained from the above control strategies are presented in subsequent sections. For each of the three scenarios, ten simulation runs were performed using different random seen numbers in the microsimulation model. A two-sample mean t-test was performed to test the significance of differences when compared to the base case.

Results for the online VSL implementation are presented in Table 4.13. A highlighted cell in the last column indicates that the difference is not significant at 90% confidence level. Throughput and speed data were collected at two locations in the test section: middle (Westover Road) and end (West 40th Street).

Table 4.13: Results of online VSL implementation

Performance Measures	Base	VSL	(VSL-Base)%	T-Test p-value
Throughput -mid (veh)	8458	8190	-3%	8.3E-05
Throughput -end (veh)	10406	10104	-3%	1.4E-04
Speed -mid (mph)	25	20	-18%	7.6E-06
Speed -end (mph)	33	27	-18%	2.1E-06
Total Travel Time(h)	2237	2346	5%	5.3E-03
# Stop/Vehicle	17	17	-1%	7.2E-01
Lane Changes	68617	48141	-30%	5.3E-03
Delay-network(sec/veh)	72	77	7%	6.1E-02
Delay-corridor(sec/veh)	363	260	-28%	8.2E-07
*CVS (with lane)	0.54	0.49	-10%	4.0E-02
*CVS (across lanes)	0.52	0.44	-17%	4.4E-02
Density (veh/mi)	0.51	0.48	-4%	6.4E-01

*CVS—coefficient of variation of speed

Average values of performance measures over ten simulation runs are presented for both the Base case and VSL case. Performance measures values for individual runs are presented in Appendices B, C, and D for difference scenarios. The fourth column in the table denotes the percent change in performance measures when compared to the base case. The last column records the p-value of two-sample mean t-test. A highlighted value in this column denotes that the difference is not significant at 90% confidence level.

4.3.4 Interpretation of results

VSL strategy does not have significant impact on the throughput of the system. This result is consistent with the existing literature, which reports that VSL does not increase the capacity of the freeway. VSL decreased the traffic speed both in the middle of the section and at the end. This resulted in a small increase in total system travel time. It decreased delay for travelers on the VSL corridor, but increased delay for other travelers (those who are entering or exiting the freeway in the middle of the test section).

The primary benefit of VSL, consistent with existing literature, is that it harmonized traffic by reducing the total number of lane changes and by reducing speed variability.

Chapter 5. Peak-period Shoulder Use

5.1 Control Strategy for Peak-period Shoulder Use

For the same reasons as in speed harmonization, we propose to use simple and transparent control strategies to govern temporary shoulder use. Furthermore, as recommend by FHWA [60], we assume that the shoulder is used only when speed harmonization is active. Before we present the specifics of the proposed control algorithm, let us discuss what we can anticipate from the use of the shoulder from a traffic flow theory perspective. A typical speed-flow curve is given in Figure 5.1. This speed-flow curve fully determines the maximum capacity of the road segment under consideration. The use of the shoulder lane is equivalent to the addition of capacity. Hence we can anticipate that the maximum capacity (i.e., the right most point on the speed-flow curve) shifts to the right. Moreover, by assumption, the speed limit is lowered, which results in the downward translation of the speed-flow curve. This process is illustrated for a different speed-flow curve in Figure 5.2. As can be seen, the curve expands to the right and contracts in the vertical direction when the speed limit is decreased to 100 km/h (62 mph). The resulting capacity is increased from about 3300 vph to more than 500 vph.

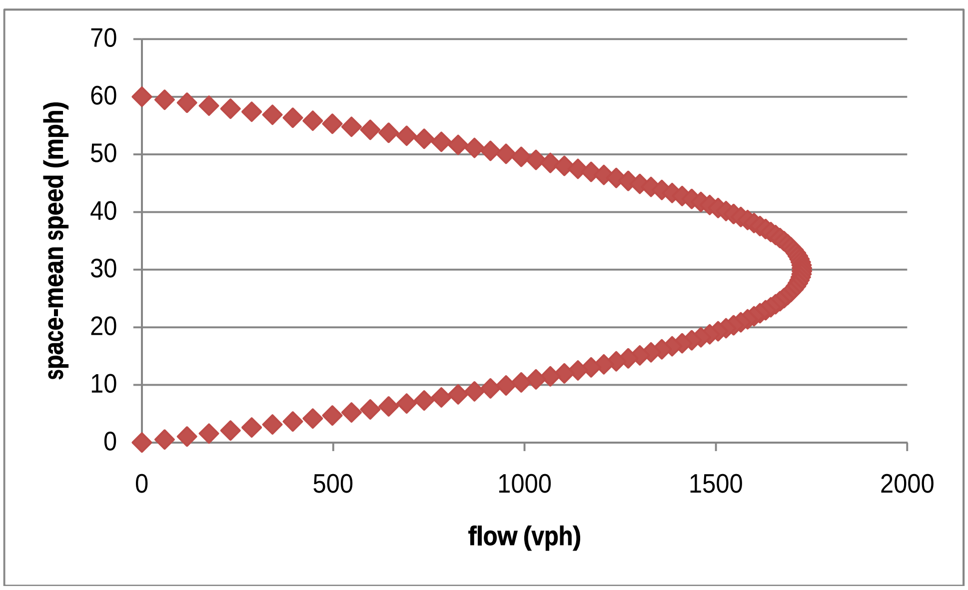


Figure 5.1: Typical speed-flow curve

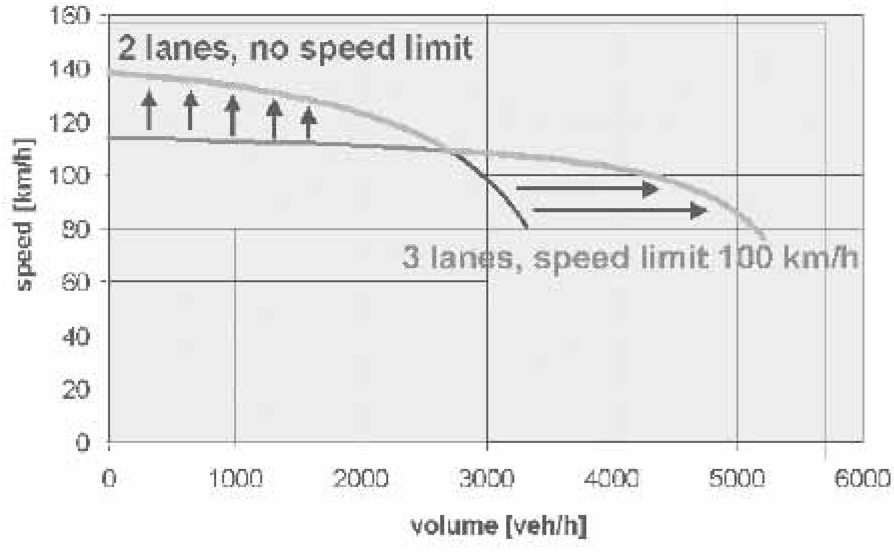


Figure 5.2: Change of the speed-flow curve due to temporary shoulder use.
Source: FHWA [60]

The generic pseudo-code for the proposed control algorithm is given as follows (recall that we assume that speed harmonization is active when calling this procedure).

5.1.2 Online Control Temporary Shoulder Use

Step 1. Check if shoulder lane is free of objects. If the shoulder lane is free, go to Step 2; otherwise, repeat Step 1 after some time.

Step 2. Open shoulder lane for traffic.

Step 3. If the average flows on the lanes are less than a pre-specified value, then close the shoulder lane.

The next subsection presents some numerical simulation results to demonstrate the effectiveness of the proposed algorithm.

5.1.3 Numerical Case Study (Shoulder Use with Offline VSL)

Again, shoulder use is implemented in conjunction with both offline VSL and online VSL. As was seen in Table 4.3, traffic level of service (LOS) during the study period of 4:00 p.m.–6:00 p.m. is "F" for most part, and it is clear that this section of Mopac is severely lacking capacity. Therefore, a decision was made to open the shoulder for the entire duration of the study.

In this case study, we consider temporary shoulder use for the same test corridor we have used in Tasks 4 and 5. In particular, we consider the use of the shoulder between Enfield Road and West 35th Street. Heavy vehicles were barred from using the shoulder. The implementation of shoulder use with offline VSL resulted in the following observations:

- Temporary shoulder use resulted in small increase in throughput (Table 5.1).

Table 5.1: Shoulder use effect on throughput

Peak-period Shoulder Use	Throughput (% change)	
	Westover Rd	W 40th St
No Shoulder Use	-	-
Shoulder Use	2.2	3.5

- Shoulder use improved traffic speed considerably where it was implemented. However, speed reduced at the end of shoulder use section due to bottleneck creation (Table 5.2).

Table 5.2: Shoulder use effect on speed

Peak-period Shoulder Use	Speed (mph)	
	Westover Rd	W 40th St
No Shoulder Use	25	34
Shoulder Use	51	25

- Peak-period shoulder use reduced total delay and stopped delay by half (Table 5.3).

Table 5.3: Shoulder use effect on delay

Peak-period Shoulder Use	Total Delay per Vehicle (% change)	Stopped Delay per Vehicle (% change)
No Shoulder Use	-	-
Shoulder Use	-45.3	-50.9

- Peak-period shoulder use reduced number of stops per vehicle by half (Table 5.4). It did not have much effect on lane changing.

Table 5.4: Shoulder use effect on stops and lane changes

Peak-period Shoulder Use	Number of Stops per Vehicle (% change)	Number of Lane Changes (% change)
No Shoulder Use	-	-
Shoulder Use	-50.0	0.2

5.1.1 Numerical Case Study (Shoulder Use with Online VSL)

Online variable speed limits were implemented simultaneously to test the benefit of this combined strategy on traffic operations and safety. Average values of performance measures over ten simulation runs and p-values for two-sample mean t-test are presented in Table 5.5.

Table 5.5: Results of VSL and shoulder use implementaion

Performance Measures	Base	VSL+SU	(VSL+SU-Base)%	T-Test p-value
Throughput—mid (veh)	8458	8591	2%	6.2E-04
Throughput—end (veh)	10406	10556	1%	6.4E-03
Speed—mid (mph)	25	26	3%	1.1E-01
Speed—end (mph)	33	21	-36%	3.6E-07
Total Travel Time(h)	2237	2332	4%	1.2E-01
# Stop/Vehicle	17	15	-13%	2.2E-02
Lane Changes	68617	53784	-22%	1.2E-01
Delay-network(sec/veh)	72	57	-21%	3.7E-04
Delay-corridor(sec/veh)	363	152	-58%	7.8E-09
*CVS (within lane)	0.54	0.05	-91%	2.7E-07
CVS (across lanes)	0.52	0.83	58%	2.5E-02
Density (veh/mi)	0.51	0.33	-35%	3.5E-03

*CVS—coefficient of variation of speed

5.1.2 Interpretation of results

As can be seen from Table 5.5, the combined strategy of VSL and shoulder use did not have any significant effect on the throughput of the freeway corridor.

However, their impacts on traffic speed in the middle of the test section and at the end are markedly different. VSL tends to decrease the traffic speed. Shoulder use results in higher speed in the middle of the section by decreasing the density of the traffic by providing more space. These two effects cancel each other in the middle of the section and therefore speed remains practically unchanged there. However, shoulder use creates a bottleneck at the end of the section. Sudden drop of shoulder use at the section end reduces the capacity of the downstream section by one lane and this leads to bottleneck creation. Moreover, vehicles from the shoulder try to merge to normal lanes, which further disrupts traffic flow. The combined VSL and shoulder use at the end of the test section results in significant drop in traffic speed. VSL and shoulder use increase the total system travel time by a small amount.

VSL and shoulder use resulted in traffic homogenization by reducing the total number of lane changes and number of stops per vehicle in the traffic stream. It also resulted in reduced speed variability with lanes and reduced density, which leads to a smoother traffic flow. However, due to additional lane changes to and from shoulder to regular lanes resulted in an increase in speed variability across lanes.

5.2 Multi-resolution Analysis

Variable speed limits and shoulder use have immediate effect on traffic condition in the test corridor. These effects are captured by a microsimulation model, and are presented in previous sections. The capacity of the test corridor changes due to implementation of these strategies. Change in freeway capacity affects route choice of users, and thus VSL and shoulder use have a larger network-wide impact. A multi-resolution analysis was performed to determine the network level effect of these strategies.

Network level effects are studied by mesoscopic models, which are better suited for large scale network analysis and are less computationally intensive. The mesoscopic model used in this research is a cell-transmission based model, and it takes three inputs to perform network analysis: travel demand data, roadway capacity, and free-flow speed. Network level impact of VSL and shoulder use have been quantified by making an equivalent change in roadway capacity of the test corridor inside the regional Austin network in the mesoscopic model (Figure 5.3).

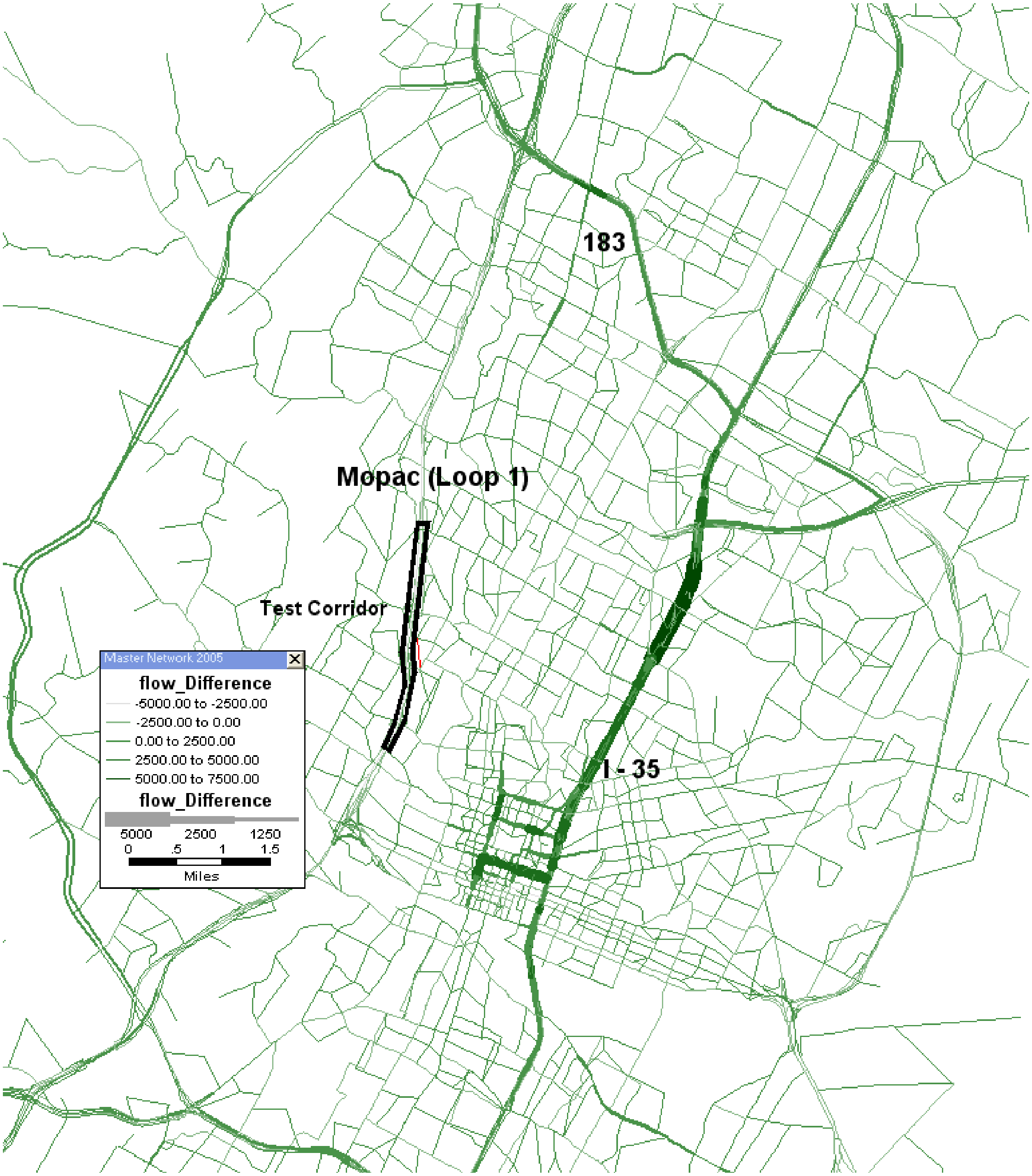


Figure 5.3: Network-wide effect on link flows (VSL & shoulder use—base case)

The results obtained after VSL and shoulder use implementation (Tables 4.13 and 5.5) indicate that there was no significant increase in throughput of freeway in the test corridor. Because the freeway is operating at or over capacity during the period of simulation (Table 4.2), it can be concluded that these strategies did not increase the capacity of the test corridor. While there was no impact on capacity due to these strategies alone, the opening of shoulder to traffic added physical space, and hence capacity, in the shoulder use section. Therefore, addition of capacity due to shoulder use was incorporated in the regional mesoscopic model of the Austin network (Figure 5.3).

Two scenarios were simulated in the mesoscopic model: base case and VSL & shoulder use implementation. Link flows for these two cases were extracted and their difference (VSL & shoulder use minus base case) is plotted in Figure 5.3. Links with thicker and darker color indicate that there was increase in their flows when VSL and shoulder use were implemented in the test corridor.

The results indicate that there was an increase in traffic using IH 35 near downtown and further up north. Correspondingly, traffic flow on arterials feeding to IH 35 in the downtown area has also increased. Mopac (Loop 1) and IH 35 are two major north-south corridors in the Austin metropolitan area. This implies that more traffic is using IH 35 to travel to and from the northern part of the city. This may be due to the adverse effect on travel time and speed that shoulder use had on traffic in the test corridor. Shoulder use created bottleneck toward the end of shoulder-use section due to sudden reduction in freeway capacity, and it led to a 36% decrease in speed there (Table 5.5). The adverse effect on flow in the test corridor may also be compounded by shorter shoulder use section in the test corridor. If shoulder is open to traffic from downtown in the south to US 183 in the north, then the test corridor is more likely to be an attractive option for travelers. In such cases, benefits obtained from better driving conditions in a longer shoulder use section are likely to outweigh the effect of bottleneck at the end of the shoulder use section.

The results obtained from multi-resolution analysis indicate that when shoulder is open to traffic for a short length, and without mitigating the negative impact of the bottleneck created, it may make the VSL and shoulder use section less attractive. However the research team cautions that a more detailed analysis should be performed before drawing strong conclusions for the network-wide impact on VSL and peak-period shoulder use.

5.3 Design Guidelines for Shoulder Lanes

Recommended design guidelines for shoulder lanes during peak traffic congestion periods are discussed in this section. These recommendations were derived using the following references: the *Texas Department of Transportation (TxDOT) Roadway Design Manual*, AASHTO *Policy on Geometric Design*, *Manual on Uniform Traffic Control Devices*, and previous case studies in which shoulders were used during peak congestion periods. The following recommendations are based on the assumption that shoulders will be used as travel lanes to manage congestion when operating speeds on freeways are 35 mph or less. This assumption is key to allowing for smaller dimensions for lane and shoulder widths than typically used for freeway segments.

Topics discussed in the following sections are typical freeway cross-section dimensions, shoulder lane width, width for the “acting” shoulder (i.e., the shoulder when the shoulder lanes are in use), pavement design for the shoulder lane, transition areas, entrance/exit ramps, accommodations for incident management, and special considerations. The dimensions and geometric considerations discussed are written from a broad perspective. Each candidate site will need to be reviewed in detail with specific design plans developed to ensure that freeway geometry, when shoulders are used as travel lanes, remains consistent with driver expectations and fits into the self-explaining roadway design.

5.3.1 Typical Freeway Cross-Section Dimensions

The *TxDOT Roadway Design Manual*, Chapter 3, Section 6 presents design criteria for freeways. The minimum lane width typically used is 12 feet. The shoulder widths vary depending on number of lanes. A four-lane facility has an inside (i.e., left-hand side) shoulder width of 4 feet and an outside shoulder width of 10 feet. A six or more lane facility has an inside and outside shoulder width of 10 feet. These dimensions along with the expected freeway operating speeds under congested periods were taken into consideration for developing the basic criteria for the shoulder lanes. These are discussed in more detail.

Shoulder Lane Width

As noted in the introduction, freeway operating speeds (i.e., 85th percentile speeds) are expected to be 35 mph or less when shoulders are used for travel lanes. These slower operating speeds allow for the shoulder lanes to be less than the typically required 12-foot width for travel lanes. Due to the slower operating speeds and change in character of the freeway under congested periods, the design criterion for shoulder lanes were developed from TxDOT's standards for freeways, urban arterials, and suburban arterials.

Based on TxDOT Roadway Design Manual for urban and suburban arterials (Chapter 3, Sections 2 and 3) and the assumed operating conditions (i.e., speeds 35 mph or less), a minimum lane width of 10 feet could be considered permissible for the shoulder lanes, if heavy vehicle volumes are low or heavy vehicles are restricted from using the shoulder lanes. To allow heavy vehicles to use the shoulder lanes, a width of at least 11 feet is desirable. A width of 11 feet for the shoulder lanes would provide approximately a 15-inch lateral distance on both sides of a typical heavy vehicle (width of 8.5 feet) between the vehicle and the edge of the shoulder travel lane.

Acting Shoulder Width

Acting shoulders are the resulting shoulders when the inside and/or outside shoulders are used as travel lanes. Based on the current design standards for shoulder widths already noted and recognizing the shoulders will be used as travel lanes during peak congested periods, we recommend a 2- to 4-foot acting shoulder (i.e., *shy distance*) measured from the edge of the shoulder lane to the edge of the paved cross-section. The 2- to 4-foot acting shoulder will provide lateral support to the shoulder lane as well as a shy distance or lateral buffer zone for vehicles to avoid medians, drainage facilities, and other roadside features beyond the paved cross-section.

Pavement

We recommend upgrading the structural composition of the pavement for the shoulder lanes to be consistent with the mainline lanes particularly if the shoulder lanes will be used during peak hours each weekday (i.e., shoulder pavement should be full depth). In highly congested areas, this could be as frequent as 4 to 6 hours per day, 5 days per week. At most this would account for 65 days in one year or 1/5 of the calendar year; therefore, upgrading the structural integrity of the shoulder lanes could be accomplished through an existing freeway maintenance schedule. The slope of shoulders should be 2% or less for driver comfort.

Transition Areas

Transition areas are the areas in which the shoulders are added (i.e., opened to vehicles for use) as travel lanes and dropped as travel lanes. We recommend using a taper rate of 10 to 1 to add the shoulder lanes for use in peak periods (i.e., open the shoulder for use at a rate of one lateral foot for every 10 feet traveled). This would effectively open the shoulder for use over a distance of 100 feet. We recommend using a taper rate of 50 to 1 to drop (i.e., close) the shoulder. This rate is consistent with the taper rates cited in the *TxDOT Roadway Design Manual*, Chapter 3, Section 6 for merging traffic from entrance ramps with the freeway mainlines. Using this rate to drop the shoulder lanes as travel lanes provides sufficient time for drivers to merge back into mainline traffic as congested periods dissipate and operating speeds exceed 35 mph; it also provides a reasonable transition when shoulder lanes must be dropped due to changes in geometry such as a narrow bridge deck where shoulders cannot be used as travel lanes.

A key consideration for transition areas is the means of enforcing the opening and closing of shoulders as travel lanes. Where shoulder lane use is repetitive during the peak hours, overhead gantries with lane use symbols are commonly used to denote whether or not the shoulder lane is open as a travel lane. However, without physical delineation or self-enforcing roadway geometry there is no guarantee the lane use symbols will be consistently obeyed. Part 6 of the *Manual on Uniform Traffic Control Devices* (MUTCD) presents temporary traffic control devices typically applied in work zones but potentially applicable in this context. For example to close the shoulder lane for use as a travel lane, an arrow panel capable of displaying chevrons indicating the need to merge into mainline traffic could be placed 200 to 500 feet in advance of the start of the taper with temporary channelizing devices placed along the taper. This configuration could be used in conjunction with overhead gantries displaying the appropriate lane use symbol.

Entrance/Exit Ramps

Freeway entrance and exit ramps, used in conjunction with the outside shoulder lane as a travel lane, present a challenging geometric environment that will be unique to each candidate site. Discussed here are some key considerations and potential solutions that can be used as starting points when considering the design and implementation for specific freeway corridors. The primary conflict related to shoulder use and entrance/exit ramps is the location where entrance ramps merge into the mainline. The interface between the gore point, the merge point, and the vehicles using the shoulder as a travel lane is a critical point of conflict at entrance ramps. The point where exiting traffic diverges from mainline traffic onto an exit ramp is operationally of less concern because vehicles are diverging rather than merging. Typically, entrance ramps are on the right-hand side therefore the outside shoulder lane will be of primary consideration; however, if there is a left-hand side entrance, the same considerations discussed would apply to the inside shoulder lane operations.

The conflict point at the entrance ramps and the outside shoulder is illustrated in Figure 5.4. The green arrows represent vehicles traveling on the outside shoulder and the red arrows represent vehicles entering on the on-ramp.

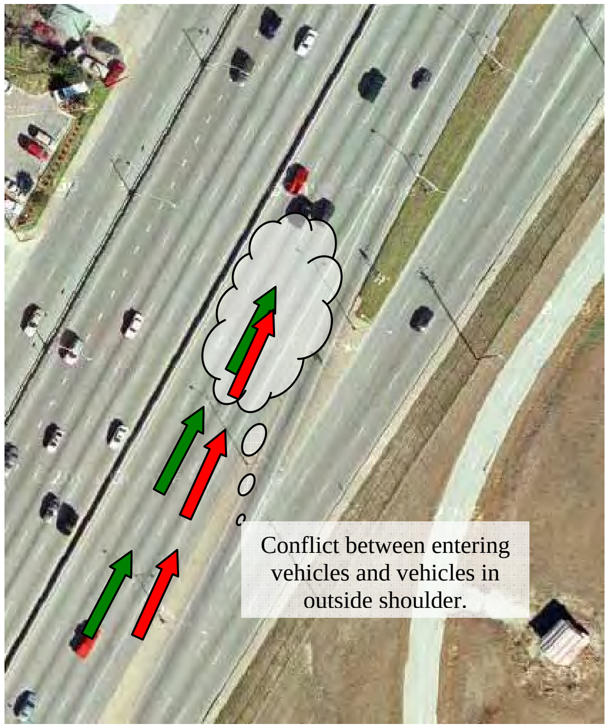


Figure 5.4: Conflict between entering vehicles and vehicles in outside shoulder lane

The conflict occurs as the entrance ramp merges into the outside shoulder creating a painted gore point where the entrance ramp lane becomes parallel with the mainline. To successfully be able to use the outside shoulder lane, right-of-way needs to be given to the vehicles traveling in the outside shoulder with vehicles merging onto the freeway yielding from the ramp. This would allow the vehicles in the outside shoulder lane to continue moving with mainline traffic. The vehicles in the outside shoulder lane would travel across the painted gore or merge area through the parallel auxiliary lane typically used as an entrance/exit lane and then back onto the painted shoulder once past the exit accompanying the entrance. Figure 5.5 illustrates this operation.

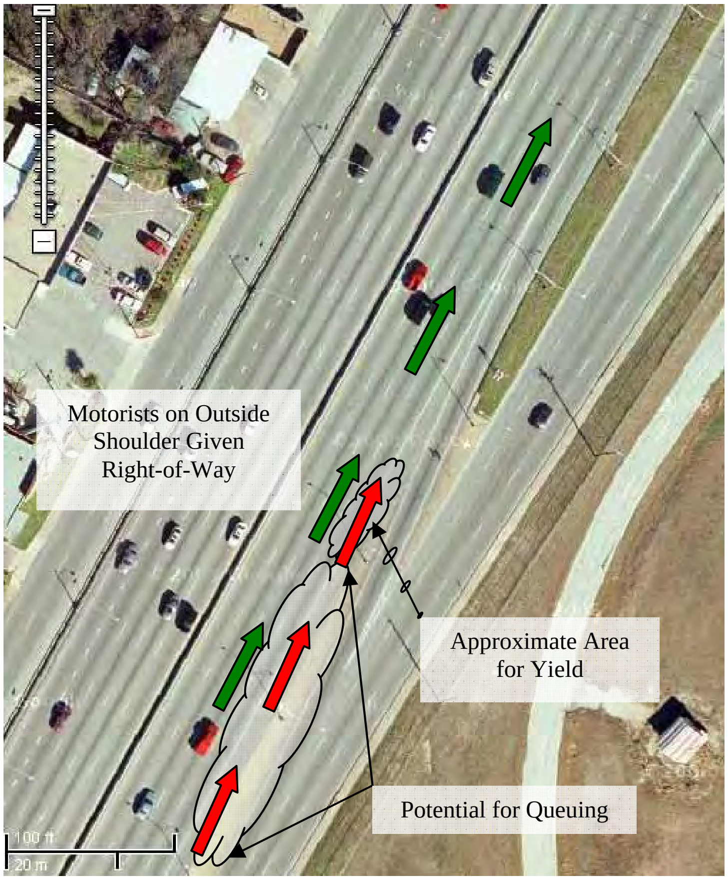


Figure 5.5: Operations with vehicles travelling in the outside shoulder

Some key considerations related to this solution are communicating these operations to the motorists and ensuring the motorists entering the freeway have ample sight distance and acceleration distance to join mainline traffic. These considerations are discussed in the following section.

5.3.2 Communicating Expected Operations to Motorists

If the outside shoulder were used as a travel lane today, the existing geometry, signs, and pavement markings would not intuitively indicate to drivers that vehicles traveling in the outside shoulder lane are permitted to drive through the painted entrance merge areas across the entrance/exit auxiliary lane and back onto the outside shoulder while entering vehicles yield to them. Potential options to communicate these operations are either static or changeable message signs, pavement markings, physical delineation markers, and/or ramp meters.

Signing

Static or changeable message signs appear the most applicable in the near term as they can be used on a temporary basis without physically impeding or changing freeway operations during off peak hours. The MUTCD does not currently contain any static signs applicable to peak period shoulder use; therefore, using changeable message signs mounted on either mobile trailers or permanent structures is one of the more readily available means to communicate with motorists in the outside shoulder lane and those on the on ramp. New traffic control devices specific for peak period shoulder use could be explored in the long term to further improve operations.

Potential locations for these signs are noted here.

- Locations for Signs for Motorists on the On-Ramp:
  - One changeable message or static sign placed shortly after the entrance to the on-ramp; and
  - A second changeable message or static sign placed at the location where vehicles on the ramp should yield.
- Locations for Signs for motorists on the Mainline:
  - Changeable message or static signs placed such that vehicles in the outside shoulder lane are able to clearly see the sign;
  - One changeable message or static sign 250 feet in advance of the entrance ramp merge; and
  - A second sign 125 feet in advance of the entrance ramp merge.

These sign locations would provide motorists on the mainline two opportunities to see and comprehend the messages. At travel speeds of approximately 35 mph, motorists would be given nearly 5 seconds from the first sign and approximately 2.5 seconds from the second sign to perceive and react to the information they're given.

This is consistent with the industry standard 2.5 seconds for driver perception-reaction time. Signing plans for candidate sites should be reviewed on a site-specific basis to ensure new signs are appropriately integrated with existing signs to prevent overloading the drivers with too much information.

Ramp Meters

If already present on the ramps, ramp meters can be used to stop oncoming traffic on the ramp, providing the right-of-way to vehicles using the outside shoulder lane. For locations without ramp meters, their addition could be an effective long-term traffic control device used with static or changeable message signs. Ramp meters could be used as a "Phase 1" treatment to manage congestion; using the shoulders as travel lanes could be "Phase 2" of congestion management. During off-peak periods, the ramp meters would be turned off and lay dark to allow for typical free flowing merge movements.

Enforcement and Education

When initially implementing peak period shoulder use for outside shoulders, it would be beneficial to have law enforcement physically present at the entrance and exit ramps to ensure motorists understand and follow the adjusted freeway operations. Similarly, a public education campaign via short TV commercials, notices on the TxDOT website, and public flyers via mail regarding the new operations during peak congestion periods would help familiarize motorists with the new operations.

Sight Distance and Acceleration

The operations discussed earlier change the merge conditions for entering vehicles from a free flowing movement to one requiring entering vehicles to slow sufficiently to yield and possibly to stop, look for an acceptable gap, and accelerate to a speed comparable to mainline operating speed to merge. These operations will only be applicable under congested periods when operating speeds are lower than typical freeway operating speeds, which will help ease the driving task for entering vehicles. These tasks also become easier when a ramp meter is present to help identify when a motorist should proceed to enter mainline traffic. However, for each entrance ramp along a candidate freeway corridor, the location of where entering vehicles should yield (or stop) will need to be determined based on the available sight distance from the ramp, whether or not the ramp will be controlled by a ramp meter, and the maximum anticipated operating speed under which the outside shoulder will be used as a travel lane.

In general, the yield (or stop) point for entering vehicles should be located where sight distance is sufficient to see a gap and acceleration distance is sufficient to reach a speed comparable to mainline traffic. Based on *TxDOT Roadway Design Manual*, Chapter 3, Section 6, freeway ramps should enable vehicles to leave and enter the mainline freeway at a speed of at least 50% of the freeway's design speed. Applying that specific design standard to this particular instance, the yield point on the on-ramp should be located to allow sufficient distance for motorists to accelerate to at least 50% of the maximum expected freeway operating speeds (e.g., 35 to 40 mph) when the outside shoulder is used as a travel lane.

5.3.3 Summary of Entrance/Exit Ramps

The primary concern regarding entrance/exit ramps and the use of the shoulder as travel lanes is the point of conflict when an entrance ramp merges into a shoulder travel lane. To reconcile this conflict, the motorists in the shoulder travel lane would need to be given right-of-way to proceed with mainline traffic and the vehicles entering the freeway would need to yield from a position on the entrance ramp. To communicate and enforce these modified operations, a combination of traffic control devices (e.g., changeable message signs, ramp metering), police presence, and public education are recommended. Each entrance/exit ramp location along each candidate freeway corridor will present unique geometry that will need to be reconciled through design plans specific to each site.

5.3.4 Incident Management

Incident management, as discussed here, consists of 1) providing a travel-way for emergency vehicles to access disabled vehicles or to serve people in need of medical attention; and 2) providing a refuge separate from the mainline travel-way for disabled vehicles to wait for assistance. Guidelines for incident management during peak period shoulder use are discussed in this section. As noted in previous sections, each candidate freeway corridor will present unique circumstances that may ease or complicate the task of providing for emergency vehicle access and disabled vehicle refuges.

Peak period shoulder use can occur under three basic conditions: 1) on a four-lane freeway with the outside shoulder being used as a travel lane; 2) on a six-lane freeway with only one shoulder used as a travel lane (either inside or outside); or 3) on a six-lane freeway with both shoulders used as travel lanes. Under scenario 2), one shoulder (either the inside or outside shoulder) is available to use as a refuge area for disabled vehicles and as a travel lane for emergency vehicles. Therefore, the following discussion will focus on scenarios 1) and 3) where the shoulder(s) typically available for emergency vehicle use and disabled vehicles are being used as travel lanes.

Emergency Vehicle Access

Emergency vehicle access should be reviewed on a case-by-case basis with access options for each candidate site identified based on the geometry and freeway access. Several potential solutions are discussed in this section.

In the presence of monitoring equipment, dynamic lane assignment symbols, and changeable message symbols, a lane or set of lanes can be closed to vehicles at the time of an incident, clearing a travel way for emergency vehicles.

Freeways with breaks in the center median would allow emergency vehicles to access an incident by traveling on the freeway section designated for the opposite direction, and crossing over to access the incident.

In the absence of these unique characteristics, emergency vehicle access can be provided by ensuring slopes adjacent to the freeway (i.e., just beyond the edge of travel way) are rounded and change at a rate of 1 vertical foot to every 6 horizontal foot (1V:6H) or flatter. This slope is negotiable by vehicles and could be used by emergency vehicles as a travel way.

There may be additional viable solutions depending on the unique characteristics along the freeway corridor.

Disabled Vehicles Refuges

Vehicle refuges provide a location for disabled vehicles to exit the travel way, call for service via a call box, and wait for service or help to arrive. Previous instances where shoulders are used as travel lanes during peak periods were accompanied by refuge areas approximately every 1/3 of a mile. A refuge area of 15 feet in width and 150 feet in length using a taper rate of 1 to 15 (i.e., develop and merge the refuge area over a distance of 225 feet) would provide sufficient space for multiple disabled vehicles and accompanying service vehicles.

5.3.5 Additional Considerations

Discussed here are additional considerations related to the design and corresponding operations of shoulder travel lanes. These considerations include the impact of horizontal curves, providing sufficient vertical clearance from overhead infrastructure, providing sufficient lateral distance from roadside objects and/or mitigating insufficient distances, freeway operations when the peak periods occur in the dark, and using intelligent transportation systems to monitor freeway operations.

Horizontal Curves

Candidate freeway corridors with frequent or long horizontal curves may require additional reconstruction (compared to tangent stretches of freeway) to accommodate use of shoulder lanes as travel lanes. Depending on the design speed of the facility and the radius of the horizontal curve, the superelevation of the inside or outside shoulder may be too steep to safely serve as a travel lane or may not be sufficiently wide to serve as a travel lane. Horizontal curves will need to be reviewed on a case-by-case basis to ensure the superelevation and cross slopes for the shoulders (in addition to the other characteristics discussed) are suitable for carrying traffic.

Vertical Clearance

Each bridge, gantry, or other structure passing over the top of a freeway will need to be reviewed to ensure sufficient vertical clearance exists over the shoulder lanes if they are to be used as travel lanes. *TxDOT Roadway Design Manual* specifies a minimum vertical clearance of 16.5 feet over the useable roadway. To use the shoulders as travel lanes, this clearance will need to be confirmed for each piece of overhead infrastructure.

Horizontal Clearance

Horizontal clearance is the distance from the edge of travel way to the nearest fixed object. When the shoulders are used as travel lanes, the horizontal clearance from the edge of the shoulder lane to the nearest fixed object should be reviewed to ensure the distance meets standards. If the distance does not meet standards, the fixed object may be moved or mitigations (e.g., crash cushions) may be identified and implemented to lessen the severity of a vehicle hitting the fixed object. *TxDOT Roadway Design Manual* cites a minimum horizontal clearance of 30 feet for freeway mainlines and 16 feet for freeway ramps in the absence of a barrier or other treatment of safety appurtenances (Chapter 2, Section 6). AASHTO's *Roadside Design Guide* presents potential roadside barriers and other safety appurtenance treatments to mitigate instances of insufficient horizontal clearance.

Freeway Operations in the Dark

During winter months, the traditional commuting peak hours do not occur in full daylight; therefore it is conceivable that the use of shoulder lanes will occur at times when drivers' visibility is relatively limited. The traffic control devices used to communicate the modified operations while peak shoulders are in use should meet night-time visibility standards as outlined by the MUTCD. Candidate sites should also be reviewed to ensure sufficient lighting is provided along the freeway corridor; adjustments, maintenance, or upgrades may be needed depending on the site.

Intelligent Transportation Systems

Intelligent transportation systems (ITS) and tools can play a beneficial role in effectively implementing, monitoring, and ensuring safe freeway operations during peak periods when shoulder lanes are in use. Traffic monitoring devices such as video cameras and loop detectors are beneficial to monitor freeway operating speeds, identify and respond quickly to incidents, and measure the level of congestion present on the freeway. This information plays a critical role in determining when, where, and for how long shoulders are used as travel lanes. This ITS infrastructure will be discussed in further detail in the technical memorandum for Task 9 regarding technology requirements. To achieve an effective system, the ITS infrastructure will need to be integrated to complement the roadway geometry and other traffic control devices present.

Chapter 6. Safety Analysis

Safety performance of a facility is a critical consideration when exploring the use of new technologies. Previous studies evaluating the variable speed limits and speed harmonization have found safety benefits in applying these strategies, particularly when employed in adverse weather conditions. In this chapter, we investigate the potential safety performance of speed harmonization and temporary shoulder use in the context of using these strategies as a congestion management tools. In particular, we identify several crash precursors to calculate the anticipated safety performance of this project's test corridor (i.e., a stretch of Loop 1 in Austin, TX) comparing safety performance without speed harmonization and shoulder use to safety performance with speed harmonization and shoulder use.

The remainder of this chapter is organized into three additional sections. In Section 6.1 we present a sample of existing literature pertaining to modeling and predicting safety on freeways. Section 6.2 reviews the crash precursors that form the basis of safety evaluation. In Section 6.3 we present numerical results for the test corridor.

6.1 Literature Review

The impact of geometric design on safety has been studied from multiple perspectives; however, by comparison, relatively limited research has been conducted on the impact of traffic operations strategies or ITS deployment on safety performance. Safety prediction methodologies and safety performance assessments are typically conducted using historical crash data to assess the influence of changes in geometry, traffic volume (volume relative to capacity), and speed limits. In the last decade, researchers have begun to explore predicting safety performance or crash potential through the use of microsimulation and surrogate measures of safety. This relatively recent development provides the opportunity to evaluate the potential safety performance of facilities due to changes in traffic flow characteristics (e.g., speed variation, queue formation, density). As will be discussed in Section 6.2, we calculate several important crash precursors developed over the last decade to calculate the anticipated facility's safety performance resulting from the changes in traffic flow characteristics brought about by implementing speed harmonization and peak period shoulder use.

Previous research examining safety and geometric design consistency was conducted by Krammes and Glascock [61] and Anderson et al. [62] . The use of historical traffic data to assess the safety of freeways has been extensively studied as well. Historical crash and traffic data has also been used to explore the relationship between traffic volumes and volume-to-capacity ratios with crash rates (63; 64; 65). The influence of speed limits on safety has been examined. Thorton and Lyles [66] are one of many sets of researchers who have explored the influence of speed limits on safety by comparing the safety performance of freeways when the speed limit is either 55 mph or 65 mph. Their study did not find a significant difference in safety performance. However, Raju et al [67], found the number of fatal accidents increases with the speed limit for a rural interstate highway in the state of Iowa.

More recent research in the last decade focusing on quantifying safety performance as a function of traffic flow characteristics includes a series of studies and papers written by Lee et al. in [68], [69], and [56]. Lee et al. (68; 69) identified four crash precursors: coefficient of variation of speed (which is defined as the standard deviation of speed divided by the mean speed) upstream of a (crash) location, average density upstream of a location, average difference in speed upstream and downstream of a specific location, and covariance of volume difference (between adjacent lanes) upstream and downstream of a specific location. Lee et al. [56] apply the crash potential function to trigger speed harmonization (i.e., change the speed limit posted via variable speed limit algorithm and related ITS infrastructure). When the crash potential exceeds a certain level, the speed limit is reduced. They found the speed harmonization beneficial for the freeway's safety performance.

Similarly, Abdel-Aty et al. [70] used matched-case control logistic regression to model the probabilities of crash for Interstate 4 in Orland, Florida. A distinction was made between crashes in the low-speed and high-speed regimes. Factors that were found to be statistically significant in contributing to crash likelihood were the coefficient of variation in average occupancy and standard deviation of volumes (for the low-speed regime) and average occupancy, and standard deviation of volumes and average volumes (for the high speed regime).

Another related approach was undertaken by Oh et al. [71]. Oh et al. [71] used loop detector data for a freeway section in California in an effort to identify reliable indicators or precursors to actual crash events. They found the standard deviation of speed 5 minutes before the crash occurrence is the best indicator for predicting an actual crash or collision. With this precursor variable, they developed probability density functions to determine whether the current traffic condition belongs to either normal or disruptive traffic conditions. Oh et al. [71] found the reducing speed variation decreases the crash likelihood.

6.2 Crash Precursors for Safety Analysis

To perform safety analysis, ideally a statistical model of crash prediction/accident potential is developed using a multiyear crash database. Such a crash database was not available for the section of Mopac studied in this project. However, researchers have identified several key crash precursors for freeways. Speed variability is the most important among them. Three crash precursors were found suitable for the purpose of this study and were adapted from Lee et al. [68].

- Coefficient of variation (c.o.v.) of speed (within lane)
- Coefficient of variation (c.o.v.) of speed (across lanes)
- Traffic density

A higher value for any of these variables indicates higher crash potential for the prevailing traffic condition. These precursors are calculated during the 5-minute period before reported accident times and compared with the non-accident case. Because a crash database was not available, safety was evaluated at a fixed time during the evening peak-period (4:40 p.m.) in the middle of the test section. Crash precursors for the VSL and VSL & Shoulder Use cases were compared with the base case. These results are presented in Section 6.3.

6.3 Numerical Case Study

The crash precursors identified earlier were calculated in the middle of the test section. To perform these calculations, traffic data (volume, speed, and occupancy) were collected by installing a loop detector in the test section in the simulation model. Changes in the values of crash precursors indicate the relative change in crash potential due to that particular variable.

Overall impact on safety can be calculated only by estimated the coefficient of these variables in a statistical model of crash prediction developed for the test section using a multiyear database.

Results for the online variable speed limits (VSL) are presented in Table 6.1.

Table 6.1: Crash precursors for VSL implementation

Performance Measures	Base	VSL	(VSL-Base)%	T-Test p-value
*CVS (within lane)	0.54	0.49	-10%	8.3E-05
CVS (across lanes)	0.52	0.44	-17%	1.4E-04
Density (veh/mi)	0.51	0.48	-4%	7.6E-06

*CVS—coefficient of variation of speed

Online VSL resulted in harmonization of traffic by reducing speed variability within lanes and across lanes. It also resulted in a small reduction in traffic density. Reduction in all these crash precursors indicates an improvement in safety conditions for the freeway.

Results for the online (VSL) and shoulder use are presented in Table 6.2.

Table 6.2: Crash precursors for VSL & shoulder use implementation

Performance Measures	Base	VSL+SU	(VSL+SU-Base)%	T-Test p-value
*CVS (within lane)	0.54	0.05	-91%	2.7E-07
CVS (across lanes)	0.52	0.83	58%	2.5E-02
Density (veh/mi)	0.51	0.33	-35%	3.5E-03

Simultaneous implementation of VSL and shoulder use resulted in great reduction in speed variability with lanes and traffic density. However, additional lane changing maneuvers to and from shoulder to regular lanes resulted in increased speed variability across lanes. The net impact of VSL and shoulder use strategy can determined if their coefficients are estimated using a historical crash database.

Based on the results presented here, it can be concluded that VSL and shoulder use have potential to make the freeway safer because of a general trend in reduction of crash precursor values for most cases. This is further supported by the observations made earlier that implementation of these strategies results in a smoother, homogenized traffic stream with a smaller number of lane changes and stops per vehicle.

Chapter 7. Recommendations on ITS, Enforcement, and Potential Impediments

In this chapter we collect a number of recommendations regarding ITS (Section 7.1), enforcement (Section 7.2) and present a discussion on potential impediments (Section 7.3) regarding the actual implementation.

7.1 Recommendations on ITS

This chapter summarizes activities conducted to survey the existing ITS technology implemented in Europe and the US, and provides some recommendations on ITS devices. ITS devices are used for traffic monitoring, information dissemination, and enforcement. We have surveyed the existing ITS technology implemented in speed control and temporary shoulder use throughout Europe and the US. The results are summarized in this section.

7.1.1 Traffic monitoring

United Kingdom, M25

In the U.K., Automatic Number Plate Recognition (ANPR) cameras have been used on M25 between junctions 28 and 27. The ANPR cameras are used for gathering flow and journey time information. The set-up of the system is as follows: two or more cameras are set up at each end of a road segment under consideration. At each station the plate recognizer unit (running Talon ANPR software) and camera collect plate reads from passing traffic. This information is then sent to a traffic management center for processing.

Netherlands, A2 Motorway

In the Netherlands, loop detectors were located every 500 m (0.3 mile) over a 12.4-mile stretch of the A2 Motorway. The posted speed is determined by a system control algorithm based on one-minute averages of speed and volume across all lanes.

Washington IH 90

The Washington State Department of Transportation (WSDOT) is operating a VSL system on IH 90 across Snoqualmie Pass. The VSL systems are Intelligent Transportation Systems that utilize traffic speed and volume detection, weather information, and road surface condition technology to determine appropriate speeds for drivers. Information for setting speed limits and for the message signs is gathered from a variety of sources. Wide aperture radar tracks speeds for feedback to the control system. All roadside data collection and control is processed through roadside cabinets.

Germany, Bavaria A7

The Line Control System operates at A7, which is a north-south axis extending from the Danish border through Germany and ending near Füssen. For traffic measurements, traffic volume and vehicle speed are detected at every observation point by inductive loops or radar sensors along the 15 km (9.3 miles) between Nesselwang and the tunnel Füssen (border with Austria).

7.1.2 Recommendation regarding traffic surveillance equipment

Based on the previous review, a monitoring surveillance system is recommended for the use of speed harmonization and peak-period shoulder usage to manage urban freeway congestion. For monitoring purposes, camera detectors are placed at an average of 1 mile, at most, for incident detection purpose. Loop detectors were used along with closed circuit camera detection in case of bad weather like fog, heavy rain, etc.

Based on former experience, if the peak-period shoulder is used at a certain segment of highway, the camera should be installed at a distance of at most 1 mile to encompass traffic detection. To help the operator, fixed movement sequences are programmed into the pivoting cameras:

- During the scanning operation, the cameras are controlled so that even small objects can be detected.
- During the release process, the Traffic Center regular carries out video monitoring of the hard shoulders.
- Unlike with the scanning operation, the cameras use the "waggle program" to show large sections of the released hard shoulder for a few seconds.
- If the operator detects a broken down vehicle during the release process, the release is cancelled for the period of time concerned.
- Shoulder won't open during bad weather, such as fog, heavy rain, etc.

7.1.3 Information dissemination

In most cases, speed information is displayed using dynamic message signs, which can be switched off or used for other display purposes. In the United States, the variable speed limit information has been typically displayed on the roadside using VMS or portable message signs.

United Kingdom, M25

On the M25 the Journey Time Management System (JTMS) is built with Talon Journey Time Analysis (JTA) and Average Speed (AS) software, which is used with the Talon ANPR engine to provide real time travel and speed information to vehicles travelling along open roads and highways and through urban and city center areas. As a vehicle is matched at the end of a road segment or outstation, the individual journey time of that vehicle is calculated.

Netherlands, A2 Motorway

The standard posted speed limit is 120 km/h (75 mph), and the variable posted speeds are 50, 70, and 90 km/h (31, 43, and 56 mph). The posted speed is determined by a system control algorithm based on one-minute averages of speed and volume across all lanes. The system covers 20 km (12 miles) with VSL signs spaced approximately every one km (0.6 mile). If an incident is detected, a speed of 50 km/h (31 mph) is displayed. If the speeds are posted with a red circle, they are enforced by photo radar. If posted without the circle, they are advisory.

Germany, Bavaria A7

The main Line Control Systems (LCS) in Germany consists of a successive installation of OP (Observation Points) and VMS (variable message signs) panels. The system includes altogether 14 display gantries, 4 variable direction signs, and 26 measurement sites outside the tunnels. Special attention must be given to an integrated technical concept between the tunnel systems and the LCS. If there is an emergency, the switching instructions will be generated by the OCT (operations control technology) and will be transmitted via the sub-center to the control units of the LCS for execution.

Washington IH 90

All roadside data collection and control is processed through roadside cabinets. Communications from the mountaintops to the control center are transmitted by microwave. All of this collected information goes to a central computer, which processes the data and determines the "safe speed" for the roadway. This system is monitored from a DOT maintenance office at the pass. Currently, a computer recommends the speed limit and an operator confirmation implements it. The speeds can vary along the corridor, and speed postings for one direction of travel may differ from those for the other direction. Inherent in the system's design is the capability for expansion, and there has been some planning to lengthen the VSL to cover more of IH 90. VSL is also being planned for portions of US-2, Stevens Pass, which also crosses the Cascades north of IH 90.

New Mexico IH 40

The project on IH 40 used variable speed signs and hazard warning signs on the right side of the road. The speed limit varied with changing conditions. VSL typically covers longer stretches of roadway, and incorporates a broad range of input criteria for speed limit decision (traffic speed, volume, crashes, congestion, construction, ice, snow, fog, etc.), which is restrained by the NMSL (National Maximum Speed Limit).

The system used a look-up table to generate the posted speed limit (see Box 1). The limit was based on the smoothed average speed plus a constant based on the environmental conditions. Negative constants were used to keep the posted speed below the 89 km/h (55mph) maximum speed limit cap.

Box 1: New Mexico's Automated Speed Control Logic

Smooth Mean Speed +/-

	Max (mi/h)	Min (mi/h)
Dry Day	+ 6.5	- 6.0
Dry Dark	+ 5.0	- 5.0
Wet Day	+ 2.5	na
Wet Dark	+ 0	na

Table 7.1 summarizes the ITS configurations detailed in this section.

Table 7.1: ITS configurations

Location	Analyze Information	Output Information
United Kingdom	Journey Time Management System (JTMS) built with Talon Journey Time Analysis (JTA) and Average Speed (AS) software	roadside portable Variable Message Signs (VMS)
Netherlands	The posted speed is determined by a system control algorithm based on one-minute averages of speed and volume across all lanes.	VSL signs spaced approximately every one km
Germany	The control and the switching of all traffic relevant systems normally take place out of the sub centre LCS A7. If there is an emergency, the switching instructions will be generated by the OCT and will be transmitted via the sub centre to the control units of the LCS for execution.	The system includes altogether 14 display gantries, four variable direction signs and 26 measurement sites outside the tunnels.
Washington	All of collected information goes to a central computer, which processes the data and determines the "safe speed" for the roadway. Currently, a computer recommends the speed limit and an operator confirmation implements it.	VSL (Variable Speed Limit) signs including hazard warning
New Mexico	After obtaining inputs (which have a broad range of criteria), the system used a look-up table to generate the posted speed limit.	VSL (Variable Speed Limit) signs and hazard warning sign

7.1.4 Recommendation regarding information dissemination devices

The combination of VMS and Portable Changeable Message Sign (PCMS) systems is recommended for information dissemination. The sign is recommended to be displayed on overhead gantries, located each mile.

7.1.5 Enforcement: Photo-radars to detect speed-limit violators

Normally speeding is controlled by the police; however, when the temporary shoulder opens, there will be no space for police officers to enforce the speeding. Photo-radar systems will provide great assistance in the use of speed harmonization and peak-period shoulder usage in managing urban freeway congestion. Table 7.2 summarizes the use of photo-radars in the Netherlands and UK.

Table 7.2: Use of photo-radars in the Netherlands and UK

Location	Tolerance/Enforcement
The Netherlands	In the Netherlands drivers can get a fine for driving 4 km/h (2.5 mph) over the speed limit, after applying a 3 or 4 km/h (1.9 or 2.5 mph) correction factor to compensate for measuring errors. Police officers are usually not allowed to use their discretion when setting the speeding threshold during enforcement activities by photo radar.
United Kingdom	In the United Kingdom, Association of Chief Police Officers (ACPO) guidelines recommend a tolerance level of the speed limit "+10% +2 mph" (e.g., a tolerance level in a 30 mph (50 km/h) zone of 35 mph). However, each police force or safety camera partnership has the ability to use its discretion when setting the levels at which drivers will be prosecuted. Photo radar uses 35mm photos.

7.1.6 Recommendation

Enforcement devices are also recommend to be placed on overhead gantries used to display VMS. These will allow violators to be automatically notified; otherwise the system will record the license plates of vehicles.

7.2 Recommendations on Enforcement

Enforcement is considered a critical piece of a successful variable speed limit program and the effective use of the shoulders as travel lanes. The primary purposes are clear: 1) to ensure compliance with the posted speed; and 2) to ensure vehicles are using the shoulders as travel lanes only when authorized. Variable speed limits appear to present a larger challenge in implementing and enforcing compared to peak period shoulder use. There are two primary ingredients for effective enforcement of variable speed limits. The first is having state law that supports variable speed limits as a regulatory speed limit for which citations can be written, if violated (as opposed to an advisory speed). The second ingredient is consistently enforcing the variable speed limit posted.

This section summarizes why enforcement is necessary for a successful variable speed limit program and peak period shoulder use. It also discusses the two key legal considerations for effectively implementing variable speed limits and liability concerns regarding variable speed limits. Recommendations based on the material reviewed to-date are provided. Finally, a set of survey questions is presented; these survey questions were distributed to jurisdictions in the United States with experience in variable speed limits and/or peak period shoulder use. Key information from the survey responses are incorporated into the recommendations related to enforcement and noted following the survey questions.

7.2.1 Why Enforcement is Necessary

Traditionally, traffic law enforcement relies heavily on deterring traffic violations through fines, which can lead to varying degrees of penalties against an individual’s license (e.g., suspension) and/or criminal record (e.g., driving under the influence). An individual’s choice to exceed the speed limit and exceed the limit by a certain amount is often made based on the perceived risk of being caught and ticketed. In the absence of consistent enforcement, motorists travel at speeds consistently higher than the speed limit. A study initiated in 2001 and conducted in Washington, D.C. and Baltimore, Maryland illustrated this behavior.

Washington, D.C. implemented automated enforcement for speeding on several surface streets. The automated speed enforcement primarily consisted of cameras triggered to take a photograph when the associated Doppler radar speed sensor indicated a vehicle was traveling faster than a preset speed [72]. A set of comparable sites in Baltimore, Maryland were left untreated. The study found that in Washington, D.C. the mean speed dropped 14% and vehicles exceeding the speed limit by more than 10 mph dropped 82% [72]. The sites in Baltimore, Maryland experienced no significant change in mean speed or the percent of vehicles exceeding 10 mph [72]. Clearly, enforcement makes a difference in driver behavior.

The ability to ensure motorists are traveling at the posted speeds when variable speed limits are being used to increase capacity (i.e., manage congestion) is paramount to its success. A primary purpose of using the variable speeds during congested periods is to create a traffic flow with as little turbulence or friction between vehicles as possible; the ideal is to have all vehicles traveling at a constant and consistent speed maximizing capacity for the facility under the given traffic and weather conditions. Variable speed limit installations in the Netherlands and Finland found camera speed enforcement critical to lowering speeds to the desired level under congested as well as adverse weather conditions [54].

Enforcing the appropriate use of peak period shoulder lanes tends to be more critical when the shoulders are not open or authorized for use. Safety concerns and conflicts could arise from motorists using the shoulders as lanes when travel speeds on the mainline are too high to warrant their use. Conflicts could also occur if vehicles are using the shoulder as a lane when the appropriate controls have not been set at the on- and off-ramps. During peak period shoulder use operations, motorists must also follow the signs and traffic control devices indicating a shoulder is no longer a useable travel lane. Failure to obey these devices when approaching a narrow bridge deck or other similar physical obstruction could easily create conflicts and disruptions in the traffic flow as vehicles try to move abruptly back into a mainline lane.

The need and value of enforcement is clear for both the variable speed limit and peak period shoulder use treatments.

7.2.2 Legal Framework Necessary for Posting Variable Speed Limits

In the context of this project, the purpose of posting variable speed limits is to reduce congestion and/or delay the onset of highly congested periods on freeways. Therefore, the speed limits posted need to be enforceable; they should be able to hold up in the court of law. In general, state law allows state or local officials to decrease speed limits if they determine the absolute speed under existing law is greater than reasonable or safe [73]. As a result, state or local officials have the ability to set revised regulatory posted speed limits applicable to all times or varying conditions. This general allowance provides for interpreting variable speed limits as regulatory speed limits; however, Hines and McDaniel [5] recommend several elements of variable speed limit legislature be in place prior to implementing variable speed limits on the roads. The purpose of these elements is to make enforcement possible and is to ensure variable speed limits will survive challenges of constitutionality that could arise. The key elements outlined by Hines and McDaniel [5] are summarized here.

1. The statutory purpose should allow a change in speed limit to protect public safety and permit the legislature to delegate to an agency power to prescribe details after they have fixed a primary policy or standard.

2. The law should require the change in the speed limit to be based on engineering and traffic investigations; in the context of variable speed limits, these would show the need for and benefit of variable speed limits under certain situations.

3. The statute must require posting for the new limit to be effective.

4. The statue must require posting of advance warning that the legal speed limit is changed ahead.

5. The law must require any information or charging documents include the existing speed limit and speed at which it is alleged the charged driver's vehicle was traveling.

6. The law might prohibit automatic enforcement within a certain distance of the new limit to allow reasonable time for driver's to adjust their speeds.

7. The law should provide broad discretion to administrative agency for enactment of regulations and sub-delegation of decision-making power.

8. Either laws or regulations should provide for certain evidence by affidavit. This means where the speed limit is decreased due to temporary hazards (e.g., traffic, weather) evidence of the reasons and the specific speed limit on the highway where the violation allegedly occurred must be presented.

The legal elements listed should be no different than the legal issues considered by courts where violations of fixed maximum speed limits occur [5].

7.2.3 Enforcing Variable Speed Limits

The two basic types of enforcement are manual enforcement and automated enforcement. Manual enforcement via police presence is generally costly and therefore sporadic; it is not a particularly effective means to consistently enforce traffic laws [72]. There are also logistical issues during highly congested periods or adverse weather, which makes manual police enforcement challenging and sometimes risky. For these and related reasons, automated enforcement is becoming increasingly popular among jurisdictions. Automated enforcement in Europe and Australia tends to be ahead of applications in the United States. The United States is faced with a different legal context, which can make automated enforcement difficult to uphold when challenged in court.

The first breakthrough in automated enforcement application in the United States has been focused around the use of red-light running cameras at signalized intersections. The state of Texas is one of the states in which red-light running cameras are in use at intersections with a previously high occurrence of red-light running incidents and/or high-speed angle crashes (which were the result of a motorist running a red-light). Many of the concerns related to automated enforcement for red-light running cameras apply to automated enforcement in general.

Therefore, many of the legal concerns related to using cameras to enforce variable speed limits and/or the appropriate use of the shoulder have already been partially addressed.

Manual Enforcement

Manual enforcement is the traditional approach to enforcing traffic laws. It can take form in a variety of ways with the simplest setup being one officer with radar of some sort to detect the speed of vehicles on the facility. This includes stationary marked or unmarked vehicles by the side of the road with radar or vascar technology or a stationary officer with detectors located across the road enabling the officer to be farther from the road. Other variations are a stationary police car plus a chase car (one officer operates the radar and the other chases down the violator), moving police vehicle using moving radar, and air patrol with an air observer and police chase cars on the ground. These strategies can be challenging to operate in periods approaching high congestion and/or adverse weather conditions. Both of these situations make it difficult for officers to chase down the vehicles and find a location to the pull them over safely. In periods approaching high congestion, a traffic stop can create the traffic flow disturbance and shockwaves that the variable speed limit program is trying to eliminate, thereby being counterproductive.

Automated Enforcement

Automated enforcement is becoming increasingly popular in the United States. Many of its uses are currently to prevent red-light running; however, it has been used to enforce speed limits, as demonstrated by the Washington, D.C. study. European countries and Australia tend to have the most experience with automated speed enforcement [72]. Automated enforcement of speeds is considered common practice in European countries particularly when using variable speed limits [54]. Cameras are mounted on the back of overhead freeway signs above each travel lane and photograph vehicles identified by speed detectors as speeding. Speed data is collected via a variety of methods including loop detectors, overhead radar, and closed circuit television [54]. The same type of technology is available in the United States; however, the legal atmosphere poses additional challenges to implementation.

Kraus and Quinoga [74] identified four critical legislative issues with regards to automated enforcement. Their paper focuses on legislative issues as related to red-light running cameras, but the same principles apply to automated enforcement of traffic laws, in general. The four critical issues identified are as follow:

1. Criminal vs. civil offense;
2. Liability of the owner or vehicle operator;
3. Privacy rights; and
4. Fine and revenue structure.

The issues identified are consistent with those identified in the Rodier et al. [75] paper regarding automated speed enforcement in the United States; however, in this paper the issue related to privacy is connected to a broader discussion of constitutionality. Criminal verses civil offense, liability of the owner or vehicle operator, constitutionality, and fine and revenue structure are discussed in this section and related to Texas State Law. Also included is a summary of potential legislation that would enable automated speed enforcement; essentially, help uphold it in a court of law.

Criminal vs. Civil Offense

Criminal and civil offenses are associated with different burdens of proof in a court of law. In a criminal offense, the burden of proof lies with the prosecution; they must prove the defendant guilty beyond a reasonable doubt. In a civil offense, the burden of proof is by preponderance of evidence; if the evidence suggests the defendant is more likely guilty than not the court may find the accused guilty unless the accused can prove innocence. This distinction makes it easier, quicker, and cheaper to try civil offenses, which carry less of a fine/penalty for those found guilty.

The distinction applies to traffic laws because moving traffic violations (e.g., speeding) is considered a criminal offense in many states. Therefore, any enforcement measures for these offenses must positively identify the vehicle and driver [74]. Using manual enforcement in which a sworn officer observes the offense this is not usually an issue. When using automated enforcement, it is now necessary to take a photo of the vehicle license plate and driver; often requiring a set-up in which the front and rear of the vehicle can be photographed. The photographic technology also becomes critical because the quality of the photo must make it possible to definitively identify the driver.

Liability

The liability issue revolves around the ability to identify the driver of the vehicle at the time of the violation. If the driver is identified by an officer or a definitive photograph, then the driver is cited for the violation regardless of car ownership. If the driver at the time of the violation is not identified then a court is able to dismiss the citation in states categorizing moving traffic violations as criminal offenses [74]. This greatly impacts the citation rate for automated enforcement. In Chandler, AZ where red-light running is considered a civil offense and automated enforcement is used, the citation rate is 83% compared to San Francisco where red-light running is a criminal offense and the citation rate is 25% [74]. Automated enforcement is more effective at dispensing citations under a civil offense interpretation of traffic law violations.

Constitutionality

The primary concerns related to violating the constitution are violating the right to privacy and freedom under the First Amendment; protection against illegal search and seizures under the Fourth Amendment; right to due process under the Fifth and Fourteenth Amendment; equal protection doctrine under the Fourteenth Amendment; and the taking clause under the Fifth Amendment [75]. However, the Supreme Court has clarified the Fourth Amendment depends on whether the person has a legitimate expectation of privacy in the invaded place and because driving is a public activity the Fourth Amendment does not apply to automated enforcement [74]. A legitimate concern does arise with the use of private information that is pulled as a consequence of the citation; therefore the photogenic evidence needs to remain confidential and limited to authorized personnel.

With regards to the remaining potential constitutional rights, legal scholars generally agree, based on the body of established law, that automated enforcement programs for traffic laws do not violate constitutional rights [75].

Fine and Revenue Structure

Past abuses of automated enforcement by equipment vendors have led to the reputation of automated enforcement as simply a revenue generator. The payment arrangements with vendors and the jurisdictions use of the revenue is related to this reputation. Some jurisdictions set up a payment structure such that vendors were paid for the equipment a flat fee and then paid to operate the system. The payment they received to operate the system was based on the number of citations issued—similar to a commission for a sales person. In San Diego and Denver, this resulted in judges ruling that this payment structure presents a clear conflict of interest to the vendors and was a wrongful delegation of responsibility by the jurisdiction [74].

Texas State Law

In Texas, a series of attempts to set up a legal structure to support automated enforcement began in 1995 with Senate Bill 1512 progressing to Senate Bill 454 in 2001 and Senate Bill 1184 in 2003. Senate Bill 1512 provided TxDOT with authorization to conduct a two-year study using automated enforcement at 10 highway railroad grade crossings [74]. Senate Bill 454 allows TxDOT and the Texas Turnpike Authority to use automated enforcement systems on toll facilities. The substantial piece of legislature creating the legal structure to use red-light running cameras was Senate Bill 1184 passed in 2003 [76].

Senate Bill 1184 grants the cities within Texas the power to issue civil citations for violations previously punishable only by criminal offenses [76]. This bill opened the door for red-light running cameras and since then their use has been seen in cities across Texas including Austin. The bill was passed with the amendment granting local authorities the power to regulate roads using "criminal, civil, and administrative enforcement" (Transportation Code, sec 542.202(b) (3)). Based on the language in Senate Bill 1184, it seems possible and reasonable that this could be extended to using automated enforcement for speed limits (variable and static) as well as the use of appropriate use of the shoulder. Review of the law by a lawyer or legislative expert is needed to confirm this deduction.

In addition to state legislation enabling local jurisdictions to prosecute traffic law violations as civil offenses, additional specific elements of legislation are recommended to enable or facilitate the ability of automated enforcement to be upheld the courts. The specific combination of enabling elements of legislation should be determined by the courts, enforcement agencies, transportation departments, motor vehicle departments, and any other agencies whose operations would be affected by the automated speed enforcement program [75]. Current states in the United States with enabling legislation for automated speed enforcement are Arizona, Arkansas, Colorado, Illinois, Maryland, Utah, Washington D.C., and Oregon [75]. Potential elements identified by Rodier et al. [75] to be included in state legislation include these:

- Definition of acceptable automated enforcement devices;
- Any restrictive uses (e.g., man vs. unmanned);
- Description of acceptable photographic evidence;
- Description of admissibility of such evidence;
- A registered owner liability section including provisions for refutable presumptions;
- Description of any required corroborating testimony;
- Provisions for summons by mail;

- Penalty provisions; and
- Specific agency empowered to operate the system.

With the passage of Senate Bill 1184, Texas State Law appears to have the necessary basics to allow for automated enforcement for speed and peak period shoulder use. It would be prudent for TxDOT to have a more formal legal review of the law to confirm this is true. If TxDOT decides to pursue automated speed enforcement, additional detailed consideration to the form and legal language for the appropriate enabling legislation would need to be determined amongst the appropriate transportation, enforcement, and legal experts. The information provided here is a broad overview of issues to be aware of, as well as potential ways to overcome these issues.

7.2.4 Potential Liability Issues

Liability concerns have been raised primarily related to the use of variable speed limits. The basic concern is the transfer of responsibility for determining a safe speed from the driver to the jurisdiction operating the variable speed limit system. Historically, the driver is responsible for choosing a safe speed at which to travel that is at, or if conditions warrant, slower than the posted speed limit. Some believe drivers will become dependent on the variable speed limits and will assume when a speed limit sign displays a typical speed then there is no danger ahead, causing them to disengage mentally from the driving task [54]. Variable speed limits in the United States have not been widely used enough or for a long enough duration to indicate whether or not this perception is true. A review of current literature did not bring to attention any specific cases with respect to liability. The variable speed limits set in this project would remain speed limits, therefore the responsibility of the driver to continue to choose a safe speed at, or if conditions warrant, below the speed limit would still apply.

7.2.5 Recommendations

Based on the material reviewed and information gathered via the survey responses we recommend confirming the elements outlined by Hines and McDaniel [5] are present in the Texas State Law Transportation Code. While the legal issues related to enforcing variable speed limits should be no different than enforcing fixed speed limits, additional legislative support would be useful if a citation for violating a variable speed limit is challenged in court.

We also recommend using automated enforcement as the primary means for enforcing the variable speed limit and peak period shoulder use. To achieve this, an investment in technology infrastructure will be necessary as well as a more formal legal review of State Bill 1184 to confirm it is applicable to speed enforcement and the proper use of the highway shoulder. We also recommend a more formal legal review of the appropriate enabling legislation specific to automated speed enforcement. Manual enforcement could be used as an interim enforcement measure until the necessary physical and legal pieces are in place; however, manual enforcement as a long-term enforcement plan is likely to be more expensive and less effective than automated enforcement.

7.2.6 Survey Questions

Listed here are a series of survey questions. These survey questions were distributed to jurisdictions in the United States that have or are currently using variable speed limits and/or shoulders as lanes during peak periods.

- Are variable speed limits currently in use in your state? If so, please state the statutory or regulatory authority for those speed limits.
- How many locations are equipped with variable speed limits and/or peak period shoulder use? For what time duration have they been in-place?
- What, if any, changes were made to state laws to allow for or to facilitate using variable speed limits and/or peak period shoulder use?
- Do local jurisdictions have the ability to cite traffic violations as civil offenses when they are considered criminal offenses under state law?
- Has the constitutionality of variable speed limits been challenged? If yes, on what grounds?
- Is automated enforcement (i.e., photo-enforcement) used to enforce the variable speed limits and/or peak period shoulder use?
    - If yes, what basic structure is used to catch violators?
    - If no, what strategies are used with manual enforcement?
- If variable speed limits are used in your jurisdiction, what advance warning is given drivers of the variable speed limit and of enforcement techniques?
  Is there any data or studies indicating the effectiveness of the enforcement approaches?
- Is there any data or studies indicating the cost of the enforcement efforts?
- If automated enforcement is used, has the constitutionality of this type of enforcement been challenged?
    - If yes, on what grounds and what was the result?
    - If there is any case law, please provide a citation or other means of identifying the case.
- Have there been any liability related lawsuits regarding variable speed limits?
    - If yes, what was the claim and outcome? And, what, if any, changes have been made as a result?
    - If no, were there any precautionary or preemptive measures taken to minimize the risk of a liability lawsuit?

These survey questions were sent to the following contacts at various public agencies in the United States.

Ted Trepanier, Washington DOT, email: TrepanT@wsdot.wa.gov
Janice Gipson, Oregon DOT, email: Janice.E.Gispon@odot.state.or.us
Rick Nelson, Nevada DOT, email: rnelson@dot.state.nv.us

Larry Senn, University of Washington, email: larsenn@u.washington.edu
Randal B Thomas, Oregon DOT, email: Randal.B.Thomas@odot.state.or.us
Steve Towen, Arizona DOT, email: stowen@dot.state.az.us
Scott Sands, FHWA, email: Scott.Sands@fhwa.dot.gov
Bill Servatius, Minnesota DOT, email: bill.servatius@dot.state.mn.us
Lisa Dumke, Consultant, email: LRDumke@addcoinc.com
LeGina Adams, New Jersey Turnpike, email: ladams@turnpike.state.nj.us
Davey Warren, FHWA, email: davey.warren@fhwa.dot.gov

Oregon and Washington DOTs provided responses from these contacts. The feedback that was provided indicated that the constitutionality of variable speed limits had not been challenged nor have they resulted in liability related lawsuits. Oregon DOT's use of variable speed limits is limited to temporary applications in and around construction zones or in emergency situations (e.g., managing wildfires). Washington DOT has two permanent variable speed limit locations, both of which are on facilities running through a mountain pass; their primary motivation is to post speed limits consistent with the prevailing weather conditions in these passes. One location is IH 90 through Snoqualmie Pass and the other is State Route 2 through Stevens Pass. Both Oregon and Washington use manual enforcement to enforce the variable speed limits; neither has data regarding compliance or effectiveness of this enforcement. Current state statutes in Oregon and Washington support their respective uses of variable speed limits. In Oregon, statues ORS 810.180(8), ORS 810.180(9), and ORS 810.200 allow Oregon DOT to determine the appropriate speed and signs to use for their temporary use of variable speed limits. In Washington, their current state statute RCW 46.61.405 (which can be viewed at http://apps.leg.wa.gov/RCW/default.aspx?cite=46.61.405) provides sufficient support to have permanent variable speed limit locations. Similarly, existing statutes in both states do not preclude the use of shoulders as travel lanes. Washington DOT's report on Active Traffic Management Concept of Operations includes their use of variable speed limits and related measures [77].

7.3 Potential Impediments

The focus of this section is to identify potential impediments to implementing speed harmonization and peak period shoulder use on Texas freeways. The key considerations regarding potential impediments for implementation in Texas are the ITS infrastructure and enforcement mechanisms. The ITS infrastructure is critical for gathering real time information for variable speed limits applicable to current traffic conditions and efficient use of the shoulder during peak congestion periods. The ITS infrastructure can also be beneficial for consistently and effectively enforcing the posted speed limit and appropriate use of the shoulder. To obtain a better and more comprehensive understanding of the potential issues Texas faces, a series of survey questions were developed and disseminated to jurisdictions and agencies (inside and outside of the United States) that have experience with speed harmonization, variable speed limits, and/or peak period shoulder use.

Presented here is an overview of the potential ITS infrastructure and enforcement impediments as well as the survey questions distributed. The survey questions were distributed to a set of potential international contacts found through the literature.

7.3.1 ITS Infrastructure Considerations

Review of the literature regarding previous implementations of speed harmonization and peak period shoulder use indicate there are several functions the ITS infrastructure serves. These are surveillance of current traffic conditions, information dissemination to the motorist, and enforcement.

Technologies used to monitor traffic conditions tend to be a mixture of inductive loop detectors, radar sensors, and cameras of varying sophistications. In the context of speed harmonization and variable speed limits, the inductive loop detectors and radar sensors tend to be used as the key infrastructure providing the data processed by the control algorithm setting the appropriate speed limit. The cameras are used to visually monitor traffic conditions and are particularly useful for ensuring the shoulder is clear for use as a travel lane as well as for identifying incidents aiding incident management efforts.

The loop detectors and radar sensors collecting information about traffic and weather conditions tend to be more densely spaced than the cameras used to visually monitor conditions. Loop detectors and radar sensors spacing depends on the application and location; frequencies of just slightly further than a quarter of mile have been used in the Netherlands. However, there may be facilities on which more or less frequent spacing seems appropriate depending on the potential fluctuations in traffic as well as the degree of saturation for the facility. Computer simulation results indicate the value of effectively implementing speed harmonization before the facility reaches capacity. To aptly time such intervention and to successfully delay the onset of highly congested conditions, a higher density of ITS infrastructure would likely be needed for facilities consistently operating near capacity.

Implementations inside and outside of the United States have consistently disseminated information to motorists via variable message signs and lane use symbols. The variable message signs display the appropriate speed limit for speed harmonization applications. They are either signs placed beside the road or displayed on overhead gantries. Literature review to date indicates the sign spacing is consistent with traditional static speed limit signs. The lane use symbols are used to indicate whether or not the shoulder is available to use as a lane. These are typically placed over the shoulder on an overhead gantry. The literature indicates these overhead gantries tend to be placed roughly every mile. In practice, the spacing will likely depend on the frequency of ingress and egress traffic as well as other roadway geometry conditions such as the inability to use the shoulder due to an approaching physical object.

ITS for enforcement tends to be a combination of radar and cameras to enable automated enforcement for speed harmonization and peak period shoulder use. For speed harmonization, radar tends to be used to measure the vehicle’s speed. If motorist is traveling faster than the tolerated speed a camera takes a picture of license plate. One such camera is generally referred to as an Automatic Number Plate Recognition (ANPR) camera. These are used in the United Kingdom. The spacing tends to be based on convenience depending on existing infrastructure conducive to providing an opportunity to deploy such technologies. For example, existing overhead gantries are typically used as a location for the ANPR with radar sensors placed at an appropriate advanced location such that the camera has sufficient time to take a photo of the vehicle violating the speed limit.

Information from survey respondents will help further pinpoint the key ITS requirements and considerations for implementation. This information will be used as a point of reference for Texas freeways.

7.3.2 Enforcement Considerations

As discussed in the previous section, consistent enforcement is considered key for effectively influencing the speeds motorists' drive. In the absence of enforcement, motorists will tend to try to drive as quickly as conditions will permit. In the context of implementing speed harmonization, this is not desirable because such behavior will continue to create turbulent traffic conditions. Turbulent traffic conditions will reduce the speed harmonization's effectiveness at delaying the onset of congestion and improving safety. In the context of peak period shoulder use, consistent enforcement ensures motorists use the shoulder only when permitted and conditions are deemed reasonable for the shoulder lane to be in use.

Manual enforcement and automated enforcement are the two primary means by which to enforce the speed limits and peak period shoulder use. As indicated in Section 7.2, manual enforcement is expensive, time consuming, and less effective than automated enforcement. Automated enforcement offers the benefits of consistency and reduces the necessary manpower to enforce speeds and peak period shoulder use. To be able to enforce the posted speed limits and peak period shoulder use via automated enforcement, Texas would need to pass legislation similar to that passed for enforcing red-light running via automated cameras. Automated speed enforcement is more common outside of the United States; however, applications abroad clearly demonstrate the technology is available and indicate its effectiveness at changing driver behavior to conform consistently to the speed limit and appropriate use of the shoulder lane.

7.3.3 Survey Questions

Listed here are a series of survey questions. These survey questions were distributed to jurisdictions and agencies outside of the United States that have or are currently using variable speed limits and/or shoulders as lanes during peak periods.

1. What ITS infrastructure was added to make speed harmonization (or variable speed limits) and/or peak period shoulder use feasible?
2. What, if any, existing ITS infrastructure was leveraged or adopted to serve speed harmonization (or variable speed limits) and/or peak period shoulder use?
3. What information is collected in the field and at what intervals (e.g., speed every three seconds at locations spaced at 500 feet)? Please be sure to describe the frequency, in space and time, at which data is collected.
4. What infrastructure or equipment does your jurisdiction use to display information to motorists regarding the variable speed limit and/or using the shoulder during the peak period?
5. How is the information displayed? Are there supplemental locations where information is displayed or provided to travelers?
6. What kind of software and hardware does your jurisdiction use to operate speed harmonization (or variable speed limit) and/or peak period shoulder use? Did your jurisdiction use simulation software for optimizing the systems in a laboratory before implementing in the field?
7. Did your jurisdiction construct new emergency refuge areas for peak period shoulder use? If yes, what design guidelines are used to construct the refuge areas (e.g., spacing, width, depth)?

8. What kind of software and hardware is being used to store and analyze the information received via ITS in the field?
9. What are the basic functions of the control algorithm used to set the speed limit and/or open or close the shoulder for use as a lane? Is their human operator oversight when the system(s) is in use?
10. In your opinion, how crucial is ITS technology to successfully implementing speed harmonization (or variable speed limits)? Please rate on a scale of 1 to 5 with 1 as not crucial to 5 as absolutely necessary. Please explain the rating you provide.
11. In your opinion, how crucial is ITS technology is successfully implementing peak period shoulder use? Please rate on a scale of 1 to 5 with 1 as not crucial to 5 as absolutely necessary. Please explain the rating you provide.

These survey questions were sent to the following contacts at various public agencies outside the United States.

Konrad Bergmeister, email: Konrad.Bergmeister@boku.ac.at
John Paynton, email: john.poynton@highways.gov.uk
Ing R. Ernst, email: Ernst@ida.tu-bs.de
Yrjo Pilli-Sihvola, email: yrjo.pilli-sihvola@tieh.fi
Graham Brisbane, email: graham_brisbane@rts.gov.nsw.au

Unfortunately, the contacts above did not provide responses to the questions provided. Our recommendations based on information found in the literature are provided in the next section.

7.3.4 Recommendations

There are two types of impediments to address: global and local. Global impediments are issues relating to the necessary legal framework to be able to implement peak period shoulder use, variable speed limits, and automated enforcement. These potential impediments affect any candidate sites or corridors under consideration. Ensuring existing statutes allow for and support these is a critical up-front task that needs to be addressed. Depending on the existing statutes, following up with additional necessary legislation is another critical task that would need to start early in the process of considering speed harmonization and peak period shoulder use implementation. Local impediments are those specific to a given candidate site or corridor. These potential impediments include considering the existing roadway cross-section, existing density of ITS infrastructure, recurring traffic conditions, traffic mix, and other site-specific characteristics. The degree to which these characteristics coincide with the geometry and ITS recommendations, presented earlier, will determine the feasibility of implementing speed harmonization and peak period shoulder use. We recommend addressing the global impediments noted earlier and then proceeding to address any potential local impediments on a case-by-case basis.

Chapter 8. Feasibility and Operational Deployment Plan

8.1 Feasibility Analysis

This section presents a cost benefit analysis (CBA) framework, which can be applied to assess the potential costs and benefits in implementing speed harmonization and peak period shoulder use on Texas freeways. The ability to assess the relative value of alternative transportation projects is a critical component in making informed decisions for transportation improvements and effective transportation plans for the future. CBA are part of many transportation studies and/or investigations into alternative solutions or projects. The detail to which they are conducted often depends on where in the overall project development process the particular alternative is situated. In earlier planning stages, CBA can be conducted at a rough, sketch-planning level with more comprehensive and detailed CBA following as an alternative enters into the design phases. At each stage of an alternative's development the CBA can serve as one means to screen alternatives and/or modify them to meet the overall project objective or vision. A useful general reference in conducting CBA is the American Association of State Highway Officials' *A Manual of User Benefit Analysis for Highways* (also referred to as the AASHTO Redbook; see [78]).

The CBA framework presented here is not specific to any particular geographical area within Texas; it is oriented towards the generic physical context of Texas freeways. In application, the actual values of the benefits and costs considered in the CBA will depend on the site specific physical and topographical characteristics. The CBA framework is discussed in the context of screening sites for implementing speed harmonization and peak-period shoulder use; the benefits and costs presented are those expected to be attributable to implementing speed harmonization and peak-period shoulder use. The overall intent of this section is to provide an overarching framework TxDOT can use as guidance when considering the potential costs and benefits associated with speed harmonization and peak-period shoulder use implementation. CBA methodologies, potential benefits and costs to consider, and a CBA framework are discussed in the following sections.

8.1.1 Cost Benefit Analysis Methodology

The basic approach for conducting a CBA is to assess the relative difference in benefits and costs associated with a given transportation project or initiative. The focus is to address the question of whether or not a transportation project or initiative is worth the monetary investment. In the course of answering or addressing this question there are number of decisions and assumptions an analyst must make that impact how the CBA is performed and its results. These basic considerations are discussed. For any analyst who has conducted a CBA before, much of this information will be familiar.

Time Period of Analysis and Alternative's Design Life

Two initial considerations are the time period for which the analyses will be conducted and the design life of the proposed project. In the context of speed harmonization and peak period shoulder use, the likely daily time period are the daily peak commuting periods. The design life associated with implementing speed harmonization and peak period shoulder use will be up to the engineer's or analyst's discretion. It is likely to depend on how far into the future he or she anticipates speed harmonization and peak period shoulder use will be employed without any other significant changes to the physical freeway or how it is operated. Time period of the analysis and design life are key parameters because the CBA will consider the total annual benefits and costs for the time periods within each year of the anticipated design life.

Converting Annual Benefits and Costs to a Present Value

The analyst or engineer will quantify the benefits and costs associated with the "do-nothing" and implementation scenarios for each year in the analysis period (the analysis period is equivalent to the proposed project's design life). The annual difference between the benefits for the two scenarios will be calculated as will be done for the annual costs. The annual benefits and annual costs will each be converted to a present value. To calculate the present value, the analyst or engineer must determine a discount rate (minimum rate of return); there is often a federal or state specified discount rate when considering government-funded projects. The annual benefits and costs are unlikely to be uniform over the course of the design life; therefore the following equation would be used to convert the non-uniform annual benefits and costs to present values.

$$PV = \sum_{y=1}^{n} [A_y*(1+i)^{-y}]$$

where, PV = present value, A = annual benefit or cost, i = discount rate, y = index for year in design life of alternative, and n = total number of years in design life.

Comparing Benefits and Costs

Once the present values of the benefits and costs are known, the analyst or engineer can compare the benefits and costs for each site via several different CBA methodologies. Potential methodologies include net present value analysis, benefit costs ratio, and cost effectiveness. These three potential approaches are discussed briefly.

Net Present Value (NPV)

The net present value method is also referred to as net present worth method. The NPV method is a simple comparison of the present value of a project's anticipated monetary benefits and costs. Mathematically, the net present value is computed by subtracting the present value costs from the present value benefits, as shown:

$$NPV = PVB=PVC$$

where, NPV = net present value, PVB = present value of benefits, and PVC = present value of costs. If the NPV is greater than zero, then the project is economically justified (i.e., the anticipated benefits are greater than the anticipated costs).

Benefit Cost Ratio (B/C Ratio)

The benefit cost ratio is similar to the NPV method in that the analyst makes use of the present value of the benefits and the costs. The primary difference is the present value benefits are divided by the present value of cost resulting in a ratio, as shown:

$$BCR = PVB/PVC$$

where, BCR = benefit cost ratio, PVB = present value benefits, and PVC = present value cost. When the benefit cost ratio is greater than 1.0, then the proposed project is considered economically justified. The higher the benefit cost ratio the more attractive the project becomes from an economic perspective.

Cost Effectiveness

Cost effectiveness measures the value an investment produces relative to a specific performance measure. It is most useful when focusing on implementing projects targeting a particular performance measure such as travel time. In such an instance, it may be useful to screen projects based on how effectively each reduces travel time for the cost of the project. The equation that would be used is:

$$\text{Cost Effectiveness} = PVC/(TT_{p,y} - TT_{o,y})$$

where, PVC = present value of cost, $TT_{p,y}$ = travel time for proposed alternative in year y, and $TT_{o,y}$ = travel time for "do-nothing" scenario in year y.

Travel time can be replaced by any performance measure to determine how cost-effective an alternative is at improving a specific measure. The obvious drawback is that this method considers only one potential benefit rather than numerous benefits captured with the NPV and B/C Ratio methods. Cost effectiveness is attractive in situations where unit cost values are not available for a performance measure.

The engineer or analyst will need to decide which is the most appropriate comparison based on the project and guidelines TxDOT may have regarding CBA. The following sections of this report discuss the specific benefits and costs to consider with regards to speed harmonization and peak period shoulder use as well as a CBA framework.

8.1.2 Benefits and Costs

Potential benefits and costs associated with speed harmonization and peak period shoulder use are discussed here. At various stages in the project development process, it may not be feasible to quantify each of the benefits and costs noted. In such instances, it reasonable to screen and/or compare alternatives as long as each CBA has been conducted to an equivalent level of detail. As alternatives progress through the project development process, it is likely to become feasible to quantify each of the benefits and costs discussed and perhaps additional ones as well. Throughout the project development process, alternatives analysis, and/or site screening process, conducting the CBA to the same level of detail for each alternative and/or site is important for equitable consideration of each alternative.

Benefits

Benefits are often used to describe measures or characteristics one hopes to improve with a proposed alternative or project. For example, travel time is a common metric used to represent congestion or delay. Transportation professionals often target reduced travel time as a primary goal or motivation for a transportation project. It is not always feasible to reduce travel time and as a result, a project or proposed alternative may result in a disbenefit associated with travel time (i.e., an increase in travel time). The relative change for each potential benefit is measured as the difference between a "do-nothing" scenario and the anticipated proposed alternative's performance at some pre-specified future year or over the course of an alternative's anticipated design life.

Table 8.1 presents a summary of potential benefits resulting from speed harmonization and peak period shoulder use.

Table 8.1: Summary of quantitative potential project benefits

Measure	Description
Travel Time	Changes in travel time for network users due to speed harmonization and peak period shoulder use (as compared to "do-nothing" scenario).
Travel Time Reliability	Change in travel time reliability due to speed harmonization and peak period shoulder use (as compared to a "do-nothing" scenario).
Emissions	Change in emissions due to speed harmonization and peak period shoulder use (as compared to a "do-nothing" scenario).
Safety	Change in crash potential due to speed harmonization and peak period shoulder use (as compared to a "do-nothing" scenario).
Fuel Consumption	Change in fuel consumption for system users due to speed harmonization and peak period shoulder use (as compared to a "do-nothing" scenario).

The measures noted in Table 8.1 are focused on characteristics that can be assessed quantitatively and converted to a common monetary unit. There are qualitative measures or non-monetary benefits the analyst may wish to consider during the site screening process; however, such considerations are beyond the scope of this CBA framework. Each potential benefit noted in Table 8.1 is discussed in further detail here.

Travel Time

Travel time savings is a potential benefit to implementing speed harmonization and peak period shoulder use. Travel time serves as a surrogate measure for reducing traffic congestion and improving mobility on the transportation system. To quantify the potential travel time savings, the analyst will need to conduct traffic analysis simulation for the "do-nothing" scenario and the proposed implementation scenario. The analyses will need to be conducted for the peak periods (morning and evening) within each analysis year. A set of simulation runs can be conducted to represent each year and then aggregated up to a total annual peak period travel time per user (see the project handbook for guidance on how to conduct such simulation). The difference between the total annual peak period travel time per user for the "do-nothing" and implementation scenario is the annual potential travel time savings. This difference can be converted to a monetary value using a value of travel time based on the amount a traveler is willing to pay per hour of travel time savings.

Many research studies have looked into the value of travel time. A recent study by Levinson and Tilahun [79] found travelers to value travel time at $7.44 per hour. The study is based on stated preference data and was used to estimate the value of travel time and travel time reliability in the context of route choice. This value of travel time is presented here as a default value that can be used within the CBA framework for speed harmonization and peak period shoulder use. The study's framework of quantifying the monetary value of travel time within a route choice context makes the value of travel time reasonably applicable for screening cites for speed harmonization and peak period shoulder use. It reflects the intuitive reasoning of the additional value (or benefit) a route with speed harmonization and peak period shoulder use can provide to travelers.

Other studies have found the value of travel time and the value of travel time reliability to vary based on trip purpose, traveler's household income, and in some instances gender and trip duration (80; 81; 82; 83; 84). However, the level of detail necessary to decipher between different driver socio-demographics, trip purpose, and trip duration is beyond the scope of this CBA. The CBA framework presented here targets a sketch-planning or screening level of analysis. If the analyst has access to travel time unit cost values specific to the proposed project area and/or additional information regarding travelers' socio-demographics and trip characteristics, more detailed and/or site specific travel time monetary values can be used in replace of the $7.44/hour found by Levinson and Tilahun [79].

Travel Time Reliability

Travel time reliability measures the variability in travel time; it is typically quantified as the standard deviation from the average travel time. To quantify travel time reliability, the average travel time for the "do-nothing" and implementation scenarios per year will need to be quantified. This can be achieved through the traffic analysis discussed in the travel time subsection of this report. More guidance on quantifying such values can be found in this project's handbook (0-5913-P1). Similar to travel time, the annual difference in travel time reliability can be found by comparing the "do-nothing" and implementation scenarios. A unit cost value for travel time reliability can then be used to convert the estimated changes in travel time reliability to monetary benefits (or disbenefits).

Similar to the value of travel time, multiple studies have been conducted and produced varying monetary value for travel time reliability. Levison and Tilahun [79] found travel time reliability to valued at $7.11/hour. As noted above, this value is presented as a default value for converting travel time reliability to a monetary value. This value is considered reasonably applicable in the context of speed harmonization and peak period shoulder use because the value is based on traveler's route choice decisions based on route performance.

Also similar to travel time, other studies have found the value of travel time reliability to vary based on trip purpose, traveler's household income, and in some instances gender and trip duration (80; 81; 82; 83; 84). As noted, the level of detail necessary to decipher between different driver socio-demographics, trip purpose, and trip duration is beyond the scope of this CBA. The CBA framework presented here targets a sketch-planning or screening level of analysis. If the analyst has access to travel time unit cost values specific to the proposed project area and/or additional information regarding travelers' socio-demographics and trip characteristics, more detailed and/or site-specific travel time reliability monetary values can be used in replace of the $7.11/hour found by Levinson and Tilahun [79].

Emissions

Emissions impacts can be quantified by pollutant for each analysis year and converted to an annual monetary value using the average effective speed, vehicle mix, and information regarding average ambient temperature and humidity. The average effective speed can be obtained from the traffic analysis discussed in the travel time and travel time reliability subsections. The analyst can use MOBILE6.2 to estimate the amount of volatile organic compounds (VOCs), carbon monoxide (CO), nitrogen oxides (NOx), carbon dioxide (CO_2), and particulate matter (PM10) emitted during the "do-nothing" scenario compared to the implementation scenario on an annual basis. Educated assumptions may need to be made regarding future vehicle mix, ambient temperature, and humidity. The total change in emissions per pollutant can be calculated using the emissions factors provided by MOBILE6.2, which are a function of roadway types, temperature, relative humidity, average effective speed, and vehicle type. The total emissions per pollutant are arrived at by multiplying the rates per vehicle type by the VMT for the vehicle type.

The difference in total annual emissions per pollutant between the "do-nothing" scenario and the implementation scenario can be converted into monetary values using unit cost estimates for each pollutant shown in Table 8.2

Table 8.2: Emissions unit cost values

Pollutant (tons)	Cost Estimate (per ton)	In 2009 dollars	Source
VOC	$4,400	$5,504	Ozbay and Berechman [85]
NOx	$10,300	$12,884	Ozbay and Berechman [85]
CO	$15	$19	Ozbay and Berechman [85]
PM10	$133,000	$166,366	Ozbay and Berechman [85]
CO_2	$50	$53	Fischer et al. [86], removal cost

Notes: Ozbay and Berechman's work is cited as the most relevant for the unit cost per pollutant because it is the most recent study found available and is cited via the Bureau of Transportation Statistics website (available at: http://www.bts.gov/publications/journal_of_transportation_and_statistics/volume_04_number_01/paper_06/html/table7.html)

Safety

The anticipated safety performance of implementing speed harmonization and peak period shoulder use can be quantified via crash potential models as discussed in Chapter 6. Using the methodology presented in Chapter 6, the analyst can estimate the potential change in the probability of crashes occurring each year. The analyst can use the traffic analysis procedures mentioned in the travel time subsection to quantify the three traffic flow metrics used to calculate crash potential. Those three metrics are the coefficient of variation of speed (i.e., speed variation within each lane), spatial variation of speed (i.e., difference in average speed at upstream and downstream locations), and covariance of volume (i.e., difference in average covariance of volume between adjacent lanes at upstream and downstream locations). These three metrics used in conjunction with the crash potential model lead to an estimated probability of crashes occurring over a specific time period. This estimated probability can be converted a number of crashes by multiplying the probability crashes occurring by the total number of vehicles on the freeway segment for the given analysis period. The analysis periods should be determined such that traffic flow conditions are relatively similar within in each period. The potential number of crashes for each analysis period can then be aggregated up to an annual estimate.

The potential change in number of crashes can be converted to a monetary value using the unit crash costs shown in Table 8.3.

Table 8.3: Unit crash costs by severity

Severity	In 2009 Dollars	Unit Cost[1]	Source
Fatality	$4,259,339.64	$4,100,000	NSC [87]
Incapacitating Injury	$216,603.00	$208,500	NSC [87]
Non-incapacitating Evident Injury	$55,267.53	$53,200	NSC [87]
Possible Injury	$26,283.24	$25,300	NSC [87]
Property Damage Only (PDO)	$2,389.39	$2,300	NSC [87]

[1] All unit costs are comprehensive costs rounded to the nearest hundred dollars. Comprehensive costs incorporate the loss of quality of life and are considered the most appropriate unit costs for calculating the value of reducing crash occurrence in the future.

The crash potential prediction model applied in Chapter 6 does not predict the severity of crashes; the model predicts the probability of crashes occurring. As a result, to convert the estimated change in the probability of crashes occurring to a monetary value, the analyst may choose to find a weighted average the values shown in Table 8.3 or may choose to assume the percent of crashes of certain severity remains unchanged in the future (i.e., the percent of PDO crashes in existing conditions is equivalent to the percent of PDO crashes under future conditions). There are obvious drawbacks to both approaches; the analyst will need to use his or her discretion to determine which is the most reasonable based on the level of detail at which the analysis is being conducted. As with all CBA, when screening multiple projects, the same assumption should be used to produce a consistent comparison.

Fuel Consumption

Fuel consumption is an out-of-pocket cost to the user and can serve as a surrogate for indicating the smoothness or turbulence of traffic flow. One of the potential benefits seen from speed harmonization is the reduction in stop and go traffic conditions. Fuel consumption for each analysis year can be calculated using the average speed during the peak periods (found via traffic analysis discussed in the travel time subsection) and the fuel consumption rates shown in Table 8.4. The analyst will need to know the basic traffic mix (light duty versus heavy trucks) for existing conditions as well as each of the future analysis years.

Table 8.4: Fuel consumption rates for light duty vehicles and heavy trucks

Average Speed	Fuel Consumption Rate (miles per gallon)[1]	
	Light Duty Vehicle[2]	Heavy Truck (FHWA Class 8)[3,4]
15	24.4	3.73
20	27.9	4.11
25	30.5	4.41
30	31.7	4.40
35	31.2	4.75
40	31.0	5.06
45	31.6	5.43
50	32.4	5.77
55	32.4	6.26
60	31.4	6.63
65	29.2	7.01
70	26.8	7.53
75	24.8	9.71

[1]Source: Davis et al. [88]

[2]Light-duty vehicles include passenger cars, sports utility vehicles, pickup trucks and minivans.

[3]Fuel consumption is for dual tires on a tractor and trailer. Fuel economy improves when singlewide tires are used instead [88].

[4]Class 8 Heavy Duty Trucks are over 33,000 pounds (15,000 kg) as defined by the Federal Highway Administration.

The difference in fuel consumption between the "do-nothing" and implementation scenarios is converted to a monetary value for each analysis year being considered in CBA. The fuel consumption rate per average speed is converted to a monetary value by multiplying the total fuel consumption (based on average speed, vehicle type, and VMT per vehicle type) by the price of fuel. Due to continuing volatility in fuel costs, the appropriate cost of fuel to be used in the analysis will be determined by the analyst.

Costs

The costs associated with implementing speed harmonization and peak period shoulder use can be categorized into three basic groups. These are capital costs, other potential initial start-up costs, and operations and maintenance. Table 8.5 summarizes the potential costs within each of the groups.

Table 8.5: Summary of quantitative project costs

Item	Description
Capital Costs	
Right-of-Way Acquisition	Costs incurred while acquiring additional right-of-way (if necessary).
Geometric Changes to Facility	Design and construction costs associated with changes to the horizontal and vertical geometry of the facility.
Signing and Pavement Marking Modifications	Design and implementation costs for modifications to upgrade or change existing signing and/or pavement markings.
ITS Infrastructure	Costs incurred to design ITS layout, purchase ITS components, and install ITS system.
Other Potential Initial Costs	
Initial Education Public Education Program	Includes costs for initial public information campaign to inform motorists of new operating procedures during congested periods.
Initial Enforcement Campaign	Costs incurred to ensure consistent, effective enforcement at onset of new operations.
Operations and Maintenance	
Monitoring ITS System Operations	Cost of monitoring system performance in real-time (while under operation).
Evaluating System Effectiveness	Cost incurred to evaluate the effectiveness of the system on a routine basis and to identify potential improvements.
Maintaining ITS Components	Includes costs for routinely maintaining and as necessary, replacing ITS components.
Maintaining Integrity of Physical Road Structure, Signs, Pavement Markings	Cost incurred to maintain the physical integrity of the facility including pavement structure, overhead structures, bridges, signs, and pavement markings.
Continuing Enforcement	Costs incurred to ensure a consistent, effective level of enforcement.

The costs summarized in Table 8.5 serve as a likely list of potential costs associated with speed harmonization and peak period shoulder use implementation. Table 8.5 is not an exhaustive list of potential costs but rather an overview of the type of costs to consider and for which to plan. Some of the costs noted may not be applicable based on the candidate site and there may be additional costs due to unique characteristics at another candidate site. Discretion should be used by the analyst when considering the potential costs and screening sites for speed harmonization and peak period shoulder use.

To remain consistent with how benefits are quantified, the costs should be quantified for the "do-nothing" and implementation scenarios on an annual basis over the course of the design life being used in the analysis.

8.1.3 Cost Benefit Analysis Framework

The project team reviewed the Federal Highway Administration's Intelligent Transportation Systems Deployment Analysis System (IDAS) software to determine if it is applicable for screening potential sites for speed harmonization and peak period shoulder use. We determined IDAS is not applicable. IDAS is currently the most pertinent software package for evaluating the impacts of ITS deployment. The software was developed for use at a sketch-planning level or screening level. It is designed to post-process information directly output by a region's travel demand model. The outputs include each of the potential benefits noted in Table 8.1. However, speed harmonization and hard shoulder running (i.e., peak period shoulder use) are not included as ITS treatments in the current version of IDAS. Therefore, IDAS is not feasible to use as a CBA or screening tool when considering speed harmonization and peak period shoulder use. An alternative framework is outlined in this section. The framework provides an overarching order in which the benefits and costs discussed above can be calculated and compared.

Consistent with many CBA, the basic approach to conducting CBA is to quantify the potential changes in performance measures (i.e., potential benefits) under a "do-nothing" scenario and an alternative "build" or implementation scenario. The difference in performance is converted to a monetary value and compared to the cost of the proposed alternative. As noted, the method for comparing the benefits and costs can be a net present value analysis, benefit cost ratio, cost-effectiveness evaluation, or another similar method. The comparison will indicate whether or not the proposed alternative is economically valid (i.e., whether or not the monetary benefits are anticipated to sufficiently outweigh the costs). A framework for conducting such analysis as related to speed harmonization and peak period shoulder use is presented here.

1) Identify candidate sites for evaluation.
2) Conduct preliminary analyses for "do-nothing" and implementation scenarios per site.
3) Identify design life to be considered in CBA.
4) Identify discount rate (minimum rate of return) to use for CBA.
5) Identify CBA comparison methodology or methodologies (e.g., NPV, B/C ratio).
6) Identify benefits to quantify.
7) Conduct more focused analyses for "do-nothing" and implementation scenarios per site to quantify annual potential benefits over the course of the design life.
8) Use outputs for "do-nothing" and implementation scenarios per site to quantify difference in performance per year of design life.
9) Convert anticipated difference in performance per year to monetary values per year of the design life and convert annual monetary benefits to a total present value.
10) Estimate difference in costs for "do-nothing" and implementation scenario per year of design life and convert annual costs to a total present value.

11) Compare present value monetary benefits and costs via chosen methodology.

This framework can be modified to fit within the standard TxDOT CBA procedures. The critical considerations with regards to speed harmonization and peak period shoulder use are quantifying the related benefits and costs. The challenge in quantifying such benefits is that a sketch-planning tool does not currently exist for such screening. Therefore, to quantify the potential benefits the analyst will need to follow the guidance in the handbook (deliverable from Task 13, 0-5913-P1) related to conducting traffic simulation analysis to obtain the necessary metrics for quantifying travel time, travel time reliability, emissions, safety, and fuel consumption. The analyst will then be able to refer to the section earlier regarding benefits to obtain guidance on how to convert the metrics to monetary values and/or software available for additional post-processing of outputs (e.g., MOBILE6.2 to convert average effective speeds to emissions).

8.1.4 Concluding Remarks

The CBA framework and considerations presented in this section are focused on methodologies, benefits, and costs applicable to implementing speed harmonization and peak period shoulder use on Texas freeways. The framework and level of detail for the analyses target a sketch-planning level or screening level evaluation suitable for identifying candidate sites likely to benefit from speed harmonization and peak period shoulder use. Potential benefits to consider include travel time, travel time reliability, safety, emissions, and fuel consumption, which collectively capture such system performance characteristics as reduced congestion and less turbulent traffic flow. Costs for consideration include initial capital costs associated with construction, right-of-way, and/or initial ITS infrastructure investments. Other initial costs for consideration are public education campaigns and focused enforcement. Finally, also considering the operations and maintenance costs over the design life of the speed harmonization and peak period should use alternative provides a solid foundation for considering the total potential costs for speed harmonization and peak period shoulder use.

Overall, this section provides an overarching framework TxDOT can use as guidance when considering the potential costs and benefits associated with speed harmonization and peak-period shoulder use implementation. Unfortunately, a sketch-planning tool or software package capable of conducting a CBA analysis for speed harmonization and peak period shoulder use does not currently exist. IDAS does not consider speed harmonization or peak period shoulder use within its suite of ITS deployment packages. As a result, the analyst will need to refer to the handbook produced as part of this project (0-5913-P1) for guidance on how to conduct the appropriate traffic analysis simulations to quantify the travel time and speed metrics necessary for assessing the potential benefits of speed harmonization and peak period shoulder use. More detailed or additional guidance regarding CBA can be found by referring to AASHTO's *A Manual of User Benefit Analysis for Highways* (also referred to as the AASHTO Redbook).

8.2 Operational Deployment Plan

This section presents an operational and deployment strategy for speed harmonization and peak period shoulder use. The strategy builds on the cost benefit analysis (CBA) framework discussed in the previous section. The operational and deployment strategy is intended to work with the CBA framework to provide a consistent means for identifying and deploying speed harmonization and peak period shoulder use to promising candidate sites. The CBA framework provides an opportunity to assess the economic validity of deploying speed harmonization and peak period shoulder use to a site. The operational and deployment plan provides information to develop the appropriate control scheme for a site, estimate a site's potential performance, identify infrastructure upgrades, create enforcement and education plans, and consider potential community impacts not directly quantifiable. Each of these elements of the operational and deployment plan is discussed below.

8.2.1 Operational and Deployment Overview

The purpose of the operational and deployment strategy is to intelligently apply speed harmonization and peak period shoulder use as a combined traffic control strategy that delays the onset of severe congestion and increases throughput. Previous deployments in other states and countries as well as traffic simulations run for this research project indicate this combined strategy is also likely to improve travel time reliability, improve safety, reduce emissions, and reduce vehicle fuel consumption. The three key pieces to realizing such benefits are to identify the sites with the most promise for improvement, develop the appropriate speed harmonization and peak period shoulder use operational scheme, and modify the existing traffic control devices and roadway geometry to support and enforce the operational scheme.

To identify sites with the most potential for success, an initial round of candidate sites or corridors will likely be identified based on the severity of the reoccurring congestion during peak commuting hours. This initial group of candidate sites can then be screened and simultaneously prepared for deployment through the following approach.

1) Develop speed harmonization and peak period shoulder schemes applicable to the candidate site based on prevailing traffic conditions and geometric data.
2) Estimate the potential performance for the candidate site; use this output to inform the CBA methodology presented in Section 8.1.
3) Identify the necessary infrastructure improvements to make deployment feasible; use this information to derive a cost estimate for deployment to be incorporated as input to the CBA methodology presented in Section 8.1.
4) Create an enforcement strategy and public education plan to complement the operational scheme developed; estimate the costs of the desired strategy and plan and include in the CBA presented in Section 8.1.
5) Consider the qualitative benefits or disbenefits of deployment to the surrounding community as well as the degree of community support.
6) Based on the outcomes of the CBA, qualitative assessment of other potential benefits and/or disbenefits and degree of community support prioritize the candidate sites.

The following sections provide additional information and guidance to make each of these steps feasible.

8.2.2 Estimating Potential Performance

Travel time, travel time reliability, safety, emissions, and vehicle fuel consumption are all performance measures for implementing speed harmonization and peak period shoulder use. As discussed in Section 8.1, each of these are potential benefits (or disbenefits) based on the candidate site's estimated performance without and with speed harmonization and peak period shoulder use . An appropriate implementation scheme must be developed to deploy a speed harmonization and peak period shoulder use strategy that is effective at improving the performance measures noted. The following sections discuss how to design an effective speed harmonization and peak period shoulder use scheme as well as how to quantify each of the performance measures noted. Once these performance measures are quantified they can be integrated into the CBA analysis discussed in Section 8.1.

Designing Appropriate Speed Harmonization and Peak Period Shoulder Use Schemes

Traffic simulation plays a crucial role in the design of speed harmonization and peak period shoulder use schemes. Hence, after the selection of a potential corridor, the first step of the analysis is to build a detailed simulation model, both of the local network (for microsimulation purposes), as well as for the "global" network (for mesoscopic simulation purposes).

Depending on the availability of sufficient ITS technologies, there are two forms of speed harmonization: online and offline. If ITS deployment is sufficiently dense, then the online version is preferred. When there is not sufficient ITS, offline algorithms are used. Many control algorithms have been proposed in the literature; however, as we have argued in Chapter 4, simple control strategies are preferred. For completeness, the online and offline control strategies are restated next (for more details we refer to Chapter 4).

To state the offline algorithm, let us first introduce some notation. In the following, let

$\bar{u}_s$ = space mean speed

n = the number of segments the selected test corridor is to be divided (parameter that can be experimentally determined with microsimulation)

$q(k)$ = flow at road segment k in vehicle per hour

$c(k)$ = capacity of road segment k

Offline Algorithm Speed Harmonization

Input $(\bar{u}_s, q)$-curves for each of the n road segments for time t of the day

Output "Speed-harmonized road segments" for time t of the day

Step 1. Pick the most downstream road segment k for which the flow almost reaches capacity.

Step 2. FOR all road segments $r = k$-1, k-2,…, 1

DO select a speed for segment r such that $q(r) < c(r+1)$

set $c(r) \leftarrow q(r)$

END

END

Step 3. When flow reduces to normal, off-peak values, reinstall original speed limits.

Online Algorithm Speed Harmonization

Input

- $(\bar{u}_s, q)$-curves for each of the n road segments. Note that we can extract the maximum capacities $c_0(k)$, k = 1, 2, .., n of the road segments from these curves.
- Current speed limits $s_0(k)$, k = 1, 2, .., n of the road segments.
- The minimum intervention duration T_{min} , *i.e.*, the minimum time interval in which the speed limit remains constant.

Output A set of dynamically changing speed limits for each of the road segments.

INITIALIZATION $c(k) \leftarrow c_0(k)$, $s(k) \leftarrow s_0(k)$

FOR $k = n, n$-1,.., 2
  IF $q(k) \approx c_0(k)$
    FOR all road segments $r = k$-1, k-2,…, 1
      DO select a speed $u(r)$ for segment r using the online VSL algorithm.
      END DO
    END FOR
  END IF
  set $c(r) \leftarrow c_0(r)$
END FOR
Display new speed limit vector $s(r)$
Wait for T_{min} time units, set $s(r) \leftarrow s_0(r)$ and repeat the algorithm.

Recall from Chapter 5 that temporary shoulder use should always be utilized in conjunction with speed harmonization.

Online Control Temporary Shoulder Use

Step 1. Check if shoulder lane is free of objects. If the shoulder lane is free, go to Step 2; otherwise, repeat Step 1 after some time.

Step 2. Open shoulder lane for traffic.

Step 3. If the average flows on the lanes are less than a pre-specified value, then close the shoulder lane.

After the execution of these algorithms, local performance can be evaluated (see below). Furthermore, based on the above results one can adjust model parameters in the mesoscopic simulation model (see Chapter 3) to obtain the network impacts, if any.

Travel Time

One of the performance measures is travel time (saving). One can focus on the travel time between specific origin-destination pairs or the network-wide travel time (global). Moreover, one can also purely examine the change in travel time on the corridor itself (local). Next we briefly indicate how the travel time savings can be measured.

Local: Run microsimulation to evaluate the total travel time before and after speed harmonization and peak-period shoulder use are applied. The difference amounts to the savings in travel time.

Global: Run a mesoscopic simulation of the entire network and evaluate the total travel time. Adjust parameters in the network-level model to reflect the changes due to the advanced traffic management strategies (see Technical Memorandum 3) and evaluate the new total travel time. The difference amounts to the saving in travel time.

Travel Time Reliability

Travel time reliability is a crucial element in the route choice process. Hence it is natural to consider it as a measure of performance. To evaluate this measure, we perform:

Local: Run microsimulation as described (i.e., under the heading “Travel Time”). Instead of evaluating the average total travel time, now the variability of the travel time should be evaluated. This can be accomplished by the calculation of the sample variances before and after the implementation of the traffic management strategies.

Global: Same as above. However, now we use the travel time data obtained from the mesoscopic simulation model to estimate the variance of travel time.

Safety

Safety is an important consideration in transportation systems. Unlike the measures already described, safety is typically a local performance measure. One should not expect to find measurable changes in safety at the network level. To measure safety, we suggest calculating several crash precursors and comparing the change in their values across different scenarios (see Chapter 6).

Ideally, a crash potential function $p(x)$ is estimated based on the specific corridor’s crash history. The evaluation of safety then simply reduces to the real-time evaluation of $p(x)$ as a function so the real-time prevailing traffic conditions x.

Emissions and Vehicle Fuel Consumption

Emissions and vehicle fuel consumption are important environmental measures to be considered. Conveniently, these data are standard output in virtually all simulation packages. There are also programs such as MOBILE and MOVES developed by the Environmental Protection Agency; these can be used to supplement simulation outputs. Key inputs for MOBILE and MOVES can be obtained from the simulation outputs discussed.

Local: Run microsimulation “before and after” and examine the differences in emissions/vehicle fuel consumption.

Global: Run mesoscopic simulation “before and after” and examine the differences in emissions/vehicle fuel consumption.

8.2.3 Identifying Infrastructure Improvements

The following sections discuss what is recommended or what has been used in the past for each infrastructure element necessary to deploy speed harmonization and peak period shoulder use. Each of these topics has been covered in additional detail in previous chapters. A synopsis is provided for ease of reference and to help guide the review of each candidate site; essentially, the analyst or engineer will compare the existing features of the candidate site to the desired features. The more the existing features match or coincide with the desired features the more attractive the site becomes based on the infrastructure present. Ultimately, the information here can be used to identify the necessary capital and operational/maintenance costs necessary for the site to be successful; this cost information feeds into the cost benefit analysis methodology presented in Section 8.1 aiding in the overall candidate site screening process.

Intelligent Transportation Systems (ITS)

As discussed in the Section 7.1, ITS is critical for providing accurate information to motorists, collecting information regarding the traffic flow, and enforcing the traffic operation controls in place. In deploying speed harmonization, ITS provides the information necessary to set the appropriate speed limit given the traffic conditions, to communicate that speed limit to motorists and to consistently enforce the speed limit. Similarly, when deploying peak period shoulder use, ITS provides information on when it is best to open and/or close the shoulder to traffic, to communicate whether or not the shoulder is open to motorists, and to consistently enforce the appropriate use of the shoulder.

ITS technologies previously used in speed harmonization and peak period shoulder use can be summarized into three categories of traffic surveillance, information dissemination, and enforcement. Table 8.6 summarizes the recommendations made in the Section 7.1 regarding each of these functions.

Table 8.6: ITS infrastructure recommendations

ITS Function	Recommendation
Traffic Surveillance	Place camera detectors at 1-mile intervals to detect incidents on the main line and shoulders. Place loop detectors at 1,500 to 2,000 foot intervals to gather data regarding traffic flow characteristics.
Information Dissemination	Place variable message signs at 1-mile intervals preferably on overhead gantries.
Enforcement	Place photo radar sensors and cameras at approximately 1-mile intervals. Take care to provide enable the system to provide motorists with ample time to respond to changes in the posted speed limit before enforcing it.

For additional details we refer the reader to Section 7.1.

Horizontal and Vertical Roadway Alignment

As noted in Section 5.3, the roadway geometry is most critical for peak period shoulder use; the deployment of peak period shoulder use changes the operational cross-section of the highway or freeway by adding the equivalent of one or two lanes of traffic. The geometric design guidelines focus on providing an overview of the primary horizontal and vertical alignment considerations applicable to deploying peak period shoulder use. The guidelines were developed in consultation with the *TxDOT Roadway Design Manual*, AASHTO’s *Policy on Geometric*

Design, and AASHTO's *Roadside Design Guide*. A key assumption made while developing these guidelines is the shoulder will be used as a travel lane under conditions in which the freeway operating speed is 35 mph or less.

Table 8.7 summarizes the basic geometric design guidelines and considerations for using the shoulders as travel lanes.

Table 8.7: Roadway geometric design guidelines and considerations

Geometric Characteristics/Considerations	Guidance
Shoulder Lane Width	10 feet with low to no heavy vehicles in shoulder lane. 11 feet to allow for more extensive use of shoulder lane by heavy vehicles.
Acting Shoulder Width	2 feet to 4 feet to provide shy distance and lateral support to pavement.
Pavement	Structural composition consistent with mainline. Cross slope 2.5% or less; maintain driver comfort, control, and ample drainage.
Horizontal Curves	Verify superelevation and width are adequate/appropriate for vehicle use.
Vertical Clearance	Verify 16.5 feet of vertical clearance across shoulder lanes; mitigate discrepancies as specified in *TxDOT Roadway Design Manual*.
Horizontal Clearance	Verify appropriate horizontal clearance of 30 feet for mainline travel and 16 feet for freeway ramps. Mitigate discrepancies via appropriate treatments identified in the *TxDOT Roadway Design Manual* and/or AASHTO's *Roadside Design Guide*.
Transition Areas (Closed to Open Shoulder and vice versa)	Open shoulder at a 10 to 1 taper (one lateral foot for every 10 feet traveled). Close shoulder at a 50 to 1 taper (one lateral foot for every 50 feet traveled).
Entrance/Exit Ramps	Implement yield control for traffic entering freeway on an auxiliary lane (see figures in Task 8 Technical Memorandum for details).
Incident Management	Provide emergency vehicle access via a case-by-case review of each site. Options include managing lanes via lane assignment controls, providing median breaks, and/or recoverable areas adjacent to freeway. Provide vehicle refuge areas every 1/3 of a mile; areas of 15 feet in width and 150 feet in length.
Freeway Operations in Dark	Verify traffic control devices in use meet night-time visibility standards outlined in MUTCD.

As is noted in Section 5.3, each candidate site is likely to present unique and challenging characteristics, solutions to which may require variations from the guidance summarized in Table 8.7 and/or presented in Section 5.3. In such situations, engineers should use their best judgment as to the appropriate mitigations. Additional details regarding these design guidelines can be found in the Task 8 Technical Memorandum.

8.2.4 Planning For Enforcement And Education

Enforcement and education are two key components to successfully implementing new traffic operations schemes. Enforcement is necessary to ensure motorists comply with the posted regulations and education is critical to ensure motorists understand what is expected of them on the roadway. Each of these components is discussed in more detail here.

Enforcement Considerations

Section 7.3 discusses enforcement considerations in particular detail. Past deployments of speed harmonization and/or peak period shoulder use have illustrated that consistent enforcement is significant in ensuring the traffic control strategy's effectiveness via speed limit compliance. Automated enforcement has been particularly effective in positively influencing drivers' tendency to obey the speed limit. Consider the following study initiated in 2001 and conducted in Washington, D.C. and Baltimore, Maryland:

> Washington, D.C. implemented automated enforcement for speeding on several surface streets. The automated speed enforcement primarily consisted of cameras triggered to take a photograph when the associated Doppler radar speed sensor indicated a vehicle was traveling faster than a preset speed [72]. A set of comparable sites in Baltimore, Maryland was left untreated. The study found that in Washington, D.C. the mean speed dropped 14% and vehicles exceeding the speed limit by more than 10 mph dropped 82% [72]. The sites in Baltimore, Maryland experienced no significant change in mean speed or the percent of vehicles exceeding 10 mph [72].

Clearly, consistent automated speed enforcement can make a significant impact on speed compliance. Speed compliance is critical for deploying a successful speed harmonization and peak period shoulder use traffic control strategy.

While there have been case studies in the United States, automated speed enforcement tends to be less common in the United States than abroad, particularly compared to European countries. Despite its scarce use in the United States, its proven effectiveness makes it a priority recommendation for successfully implementing speed harmonization and peak period shoulder use. Section 7.3 discusses some of the obstacles facing automated speed enforcement in the United States as well as recommendations in developing the legal framework necessary to use automated enforcement techniques in the United States. Listed here are the key elements of variable speed limit legislation recommended by Hines and McDaniel [5] in their National Highway Cooperative Research Project (NCHRP) publication entitled *Judicial Enforcement of Variable Speed Limits*:

1. The statutory purpose should allow a change in speed limit to protect public safety and permit the legislature to delegate to an agency power to prescribe details after they have fixed a primary policy or standard.
2. The law should require the change in the speed limit to be based on engineering and traffic investigations; in the context of variable speed limits, these would show the need for and benefit of variable speed limits under certain situations.
3. The statute must require posting for the new limit to be effective.

4. The statue must require posting of advance warning that the legal speed limit is changed ahead.
5. The law must require any information or charging documents include the existing speed limit and speed at which it is alleged the charged driver's vehicle was traveling.
6. The law might prohibit automatic enforcement within a certain distance of the new limit to allow reasonable time for driver's to adjust their speeds.
7. The law should provide broad discretion to administrative agency for enactment of regulations and sub-delegation of decision-making power.
8. Either laws or regulations should provide for certain evidence by affidavit. This means where the speed limit is decreased due to temporary hazards (e.g., traffic, weather) evidence of the reasons and the specific speed limit on the highway where the violation allegedly occurred must be presented.

For additional details and information, please refer to Section 7.3.

Education Considerations

Public education for new operating strategies and traffic control devices can be useful in proactively informing the public of what is expected of them under certain conditions. Deploying speed harmonization and peak period shoulder is likely to result in modifying the character and appearance of the roadway as well as implementing new signs or traffic control devices intended to convey critical information to motorists. In addition to traditional public outreach meetings, simple informational flyers included in utility bills, short T.V. commercials, public announcements via radio, and informational flyers made available for pickup at grocery stores, schools, and libraries can make it easier for motorists to understand the purpose for the changes, what is expected of them, and the benefits intended to come out of the new traffic control strategies. Studies regarding past speed harmonization and peak period shoulder use deployment have not explicitly discussed an education component; however, it seems clearly beneficial to consider such a component when altering some of the basic operational characteristics motorists' may take for granted.

8.2.5 Considering Qualitative Characteristics and Community Support

Thus far feasibility and deployment considerations have been focused on quantifiable benefits and costs; however not all potential impacts can be quantified, but are still worth considering qualitatively. Many of these measures are complex and are related to societal considerations not immediately conducive to representing with a numerical value (e.g., community cohesion). There are a few measures, such as noise, that can be quantified with more detailed analysis; however, this detailed analysis necessary may be beyond the scope of many screening exercises. To be able to capture these measures in some form during the screening and deployment process, the analyst can qualitatively assess them.

Table 8.8 summarizes potential qualitative measures for consideration.

Table 8.8: Potential qualitative characteristics

Measure	Description
Noise	Anticipated change in noise pollution due to change in traffic volume and/or mix to traffic.
Accessibility	Ability to access basic services (e.g., schools), employers, quality of life destinations (e.g., shopping), and local access (e.g., sidewalks).
Community Cohesion	The degree to which existing neighborhoods, communities, and recreational areas remain intact. Considers residents and local businesses necessary to relocate and/or residents and local businesses isolated from the community.
Equity	Distributive effect of the proposed project; what is the investment's impact across societal groups?
Environmental Considerations	Impacts on water resources, wetlands, habitats of endangered/threatened species, and other similar considerations.
Regional Development/ Economic Effects	Assessment of whether proposed project would attract new development or employers to the region.
Aesthetics	Visual impact of proposed project compared to "do-nothing" scenario.

The measures listed are not exhaustive nor will they be applicable for all candidate sites. Table 8.8 is provided as a reference to help guide the conscious and consistent consideration of welfare measures not conducive to quantifying numerically.

In addition to considering the qualitative measures noted, holding public meetings to gather thoughts from the community and gage community support is likely to be particularly useful in identifying candidate sites most conducive to speed harmonization and peak period shoulder use. As with many transportation initiatives, gaining community support can be a powerful catalyst in implementing new traffic control strategies.

8.2.6 Summary

The operational and deployment strategy presented here is intended to guide decisions to deploy speed harmonization and peak period shoulder use to candidate sites most likely to benefit from such strategies. The plan presents a framework for developing effective speed harmonization and peak period shoulder use schemes as well as assessing the potential performance of a candidate site, the necessary infrastructure upgrades, and the corresponding enforcement and education plans. Coupled with the CBA framework presented in Section 8.1, the operational deployment strategy provides a holistic approach to screening candidate sites while simultaneously preparing for successfully implementing speed harmonization and peak period shoulder use.

Chapter 9. Conclusions

Speed harmonization and peak-period shoulder use are promising dynamic traffic management strategies for dealing with the increasing levels of congestion observed around the globe. In this report we investigated their uses on Texas freeways. To this end, we developed a comprehensive approach to determine the feasibility of these active traffic management strategies. In particular, we presented a multi-resolution simulation framework, developed efficient control algorithms, presented several crash precursors to assess safety, and made recommendations on the ITS devices requirement and enforcement. We also discussed potential impediments in their implementations. A cost-benefit methodology has been presented to determine economic viability of these strategies. We have summarized these crucial steps in a comprehensive operational deployment plan.

Variable speed limits (VSL) and shoulder use were implemented in the test section under four different strategies (offline VSL, online VSL, offline VSL with shoulder use, and online VSL with shoulder use) to assess their impact on traffic operations and safety. The results obtained from the implementation of VSL and shoulder use are summarized here:

- VSL and shoulder use did not have significant impact on throughput of the freeway.
- These strategies homogenized traffic stream and resulted in smoother flow of traffic by reducing the total number of stops per vehicle, stopped delay, and number of lane changing maneuvers.
- In general, traffic stream was further homogenized due to reduction in traffic density and speed variability within and across lanes. This also indicated to potential safety benefits that can be obtained by the use of these strategies on freeways.
- If VSL and shoulder strategies are implemented early on and before the onset of full congestion, then they resulted in greater benefits.
- Shoulder use contributed significantly to traffic homogenization process in the middle of the shoulder-use section. However sudden drop of shoulder use at the section end reduced the capacity of the downstream section by one lane and this led to bottleneck creation and significant speed reduction.
- VSL and shoulder use implementation reduced average speed of traffic in the implementation section, and therefore they contributed to a small increase in travel time.

In conclusion, VSL and shoulder use homogenized traffic and reduced stop-and-go traffic condition by moving the traffic more steadily. Smoother flow of traffic results in less emission, less fuel consumption, and less wear and tear for vehicles, and leads to safer driving conditions.

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Appendix A: Vehicle Actuated Programming (VAP) Source Code

```
PROGRAM Spl_VMS; /* Q:\VISSIM\DATEN\_PTV\VBA\Spl_VMS.vv */

VAP_Frequency 1;

CONST
  F = 2.0,
  DT = 1,
  ALPHA = 0.5,
  Qon = 1200,
        Interval = 300; /* time interval at which VSL will check conditions */

/* ARRAYS */

/* SUBROUTINES */

/* PARAMETERS DEPENDENT ON SCJ-PROGRAM */

/* EXPRESSIONS */

/* MAIN PROGRAM */

 IF NOT initialized THEN
        initialized := 1;
        desSpeed := 65;

        /* Initialize speeds at VSL locations */
        set_des_speed(18, 10, desSpeed); set_des_speed(18, 20, desSpeed);
        set_des_speed(19, 20, desSpeed); set_des_speed(19, 20, desSpeed);
        set_des_speed(20, 20, desSpeed); set_des_speed(20, 20, desSpeed);

        SumSpeed :=0;          /*To calculate ave. speed over many loops for a single loop of
"Interval"; AvSpeed = SumSpeed/ NumVeh*/
        NumVeh :=0;

        Set_sg_direct( 1, Off );
        Start( evalInt )
 END;



        Detect:= (Detection( 1 ) + Detection( 2 ) +Detection( 3 ) +Detection( 11 ) +Detection( 12
) +Detection( 13 ) );

        IF Detect > 0 THEN
```

```
	SumSpeed := SumSpeed + (Velocity( 1 )*Detection( 1 ) + Velocity( 2 )*Detection( 2 ) +
Velocity( 3 )*Detection( 3 )+
		Velocity( 11 )*Detection( 11 ) + Velocity( 12 )*Detection( 12 ) + Velocity( 13
)*Detection( 13 ));
	NumVeh := NumVeh + Detect;

	END;

 IF evalInt = Interval*DT THEN

	qCarPrev := qCar; qHGVPrev := qHGV;
	qCar1 := Front_ends( 1 ) * (3600/Interval) / DT;
	qCar2 := Front_ends( 2 ) * (3600/Interval) / DT;
	qCar3 := Front_ends( 3 ) * (3600/Interval) / DT;
	qCar := qCar1 + qCar2 + qCar3;

	qCarZ := (ALPHA * qCar) + ((1.0 - ALPHA) * qCarPrev);
	Clear_Front_ends( 1 ); Clear_Front_ends( 2 );
	Clear_Front_ends( 3 );

	qHGV1 := Front_ends( 11 ) * (3600/Interval) / DT;
	qHGV2 := Front_ends( 12 ) * (3600/Interval) / DT;
	qHGV3 := Front_ends( 13 ) * (3600/Interval) / DT;
	qHGV := qHGV1 + qHGV2 + qHGV3;

	qHGVZ := (ALPHA * qHGV) + ((1.0 - ALPHA) * qHGVPrev);
	Clear_Front_ends( 11 ); Clear_Front_ends( 12 );
	Clear_Front_ends( 13 );

	Qb := qCarZ + F*qHGVZ;
	Q_tot := (Qcar+QHGV)*(Interval/3600)*DT;

	flow := Qb/3; /*flow per hour per lane vphpl */

	Occ := (Occup_rate( 1 ) + Occup_rate( 2 ) +Occup_rate( 3 ) )*100/3;


	IF NumVeh > 0 THEN
		AvSpeed := (SumSpeed/NumVeh)* 2.236936; /*Unit conversion from m/s to
mph */
		Q_5min := NumVeh;
	ELSE AvSpeed :=0; Q_5min := NumVeh;
	END;

	SumSpeed :=0;
```

```
        NumVeh :=0;


        Reset( evalInt ); Start( evalInt );

        /* Calculate average time mean speed */

        IF flow <= Qon THEN
                IF Occ <= 15 THEN
                        desSpeed := 65
                ELSE IF AvSpeed > 50 THEN
                                desSpeed := 65
                                ELSE IF ( (AvSpeed <= 50) AND (AvSpeed >= 40)) THEN
                                        desSpeed := 50
                                ELSE desSpeed := 40
                                END;
                        END;
                END;
        END;

        ELSE IF flow > Qon THEN
                IF AvSpeed > 50 THEN
                        desSpeed := 65
                        ELSE IF ( (AvSpeed <= 50) AND (AvSpeed >= 40)) THEN
                                desSpeed := 50
                        ELSE desSpeed := 40
                        END;
                END;
        END;


END;

Set_des_speed( 18, 10, desSpeed); Set_des_speed( 19, 10, desSpeed);
Set_des_speed( 20, 10, desSpeed);
Set_des_speed( 18, 20, desSpeed); Set_des_speed( 19, 20, desSpeed);
Set_des_speed( 20, 20, desSpeed);
Record_value( 1, flow ); Record_value( 3, Occ);Record_value( 2, desSpeed);
Record_value( 4, SumSpeed ); Record_value( 5, NumVeh); Record_value(6, AvSpeed);
        Record_value(7, Q_tot);Record_value( 8, Q_5min)
.
/*---------------------------------------------------------------------------*/
```

Appendix B: Simulations Results for Base Case

		Run Number	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10
		Random Seed Number	1	6	11	16	21	26	31	36	41	46
Performance Measures	Average Value											
Lane Changes	68617.10		69099.00	69789.00	70097.00	70470.00	65063.00	67793.00	70346.00	68122.00	66196.00	69196.00
Travel Time(h)	2236.76		2219.40	2151.76	2309.54	2215.07	2582.53	2136.20	2112.68	2201.20	2180.35	2258.88
# Stop/Vehicle	16.90		16.81	15.99	17.23	16.22	21.13	15.92	15.33	16.21	17.36	16.76
Delay	71.74		71.66	65.80	69.08	66.90	83.48	74.61	65.98	71.03	78.70	70.11
Throughput DC2	8457.50		8444.00	8438.00	8539.00	8503.00	8580.00	8392.00	8427.00	8429.00	8291.00	8532.00
Throughput DC3	10406.10		10360.00	10332.00	10451.00	10507.00	10626.00	10321.00	10375.00	10390.00	10178.00	10521.00
Speed DC2	24.94		23.24	24.69	25.88	24.44	27.11	24.82	24.86	23.85	23.09	27.38
Speed DC3	33.08		34.71	34.70	32.57	33.52	25.12	34.56	34.87	33.84	34.86	32.09
TotDelay/Veh	362.79		380.00	352.60	320.30	371.50	386.30	384.40	358.90	350.20	415.40	308.30
StoppedDelay/veh	47.30		48.80	44.50	39.40	44.20	49.40	56.60	45.40	43.50	59.70	41.50
CVS (within lane)	0.54		0.55	0.51	0.56	0.59	0.53	0.65	0.50	0.47	0.52	0.55
CVS (across lanes)	0.52		0.62	0.45	0.49	0.53	0.39	0.40	0.56	0.54	0.60	0.65
Density	0.51		0.51	0.49	0.47	0.76	0.46	0.52	0.43	0.33	0.65	0.44

Appendix C: Simulations Results for Online VSL

		Run Number	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10
		Random Seed Number	1	6	11	16	21	26	31	36	41	46
Performance Measures	Average Value											
Lane Changes	48140.70		48418.00	46737.00	49765.00	47873.00	49989.00	44597.00	47543.00	48513.00	49393.00	48579.00
Travel Time(h)	2346.30		2313.87	2268.98	2194.34	2333.34	2740.84	2318.94	2294.07	2215.29	2352.19	2431.17
# Stop/Vehicle	16.70		15.85	15.64	13.43	17.30	21.52	17.50	16.67	14.34	17.17	17.60
Delay	76.89		72.85	73.93	59.24	80.38	93.57	84.19	75.83	66.50	81.14	81.29
Throughput DC2	8189.50		8266.00	8207.00	8377.00	8043.00	8349.00	7998.00	8045.00	8230.00	8219.00	8161.00
Throughput DC3	10104.40		10199.00	10103.00	10291.00	9984.00	10261.00	9903.00	9910.00	10189.00	10093.00	10111.00
Speed DC2	20.45		20.29	20.24	21.29	20.43	20.18	20.29	20.23	20.87	20.51	20.20
Speed DC3	27.20		27.61	27.67	27.67	27.69	23.26	27.73	27.76	27.78	27.24	27.56
TotDelay/Veh	259.53		256.60	260.40	186.50	287.50	284.60	307.10	254.50	226.50	276.20	255.40
StoppedDelay/veh	51.67		48.60	53.30	32.30	60.80	53.00	67.60	48.90	42.40	57.40	52.40
CVS (within lane)	0.49		0.49	0.43	0.48	0.49	0.34	0.56	0.45	0.49	0.61	0.53
CVS (across lanes)	0.44		0.35	0.42	0.58	0.51	0.38	0.43	0.37	0.46	0.45	0.43
Density	0.48		0.41	0.49	0.50	0.47	0.58	0.45	0.45	0.44	0.47	0.58

Appendix D: Simulations Results for Online VSL & Shoulder Use

		Run Number	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10
		Random Seed Number	1	6	11	16	21	26	31	36	41	46
Performance Measures	Average Value											
Lane Changes	53783.50		52913.00	53462.00	54481.00	53846.00	55481.00	53611.00	53276.00	52025.00	55436.00	53304.00
Travel Time(h)	2331.70		2240.81	2265.16	2148.26	2301.16	2361.97	2349.71	2270.64	2501.66	2341.10	2536.57
# Stop/Vehicle	14.70		12.84	13.83	11.38	14.08	15.30	14.56	13.98	17.24	15.21	18.56
Delay	56.64		49.17	54.78	44.50	53.73	59.58	55.71	54.45	65.91	57.32	71.24
Throughput DC2	8591.10		8592.00	8594.00	8579.00	8574.00	8602.00	8607.00	8597.00	8603.00	8568.00	8595.00
Throughput DC3	10556.00		10608.00	10533.00	10650.00	10621.00	10564.00	10625.00	10492.00	10489.00	10510.00	10468.00
Speed DC2	25.72		25.50	26.80	26.60	25.50	25.70	25.30	26.20	25.50	24.60	25.50
Speed DC3	21.12		21.90	20.80	21.30	21.20	20.90	21.30	21.10	21.00	21.00	20.70
TotDelay/Veh	151.91		130.20	145.50	118.10	148.90	160.70	153.00	150.90	170.20	171.70	169.90
StoppedDelay/veh	25.24		21.30	24.90	18.90	23.50	27.20	26.70	24.60	28.20	29.00	28.10
CVS (within lane)	0.05		0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.13	0.28	0.01
CVS (across lanes)	0.83		0.41	0.81	0.55	0.95	0.64	0.90	0.62	1.13	1.64	0.65
Density	0.33		0.26	0.35	0.33	0.31	0.29	0.28	0.28	0.45	0.39	0.33