NCHRP 3-83

Low-Cost Improvements for Recurring Freeway Bottlenecks

Draft Final Report

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CHAPTER 1
INTRODUCTION

Freeway congestion delay consists of recurrent delay plus the additional (non-recurrent) delay caused by accidents, breakdowns, and other random events, such as inclement weather and debris. Recurrent delay arises when traffic demands exceed the freeway capacity (bottlenecks), fluctuations in demand, the manner in which the freeway is operated, as well as the physical layout of the freeway. Non-recurrent delay depends on the nature of the incident: an accident is likely to cause more delay than a vehicle stopped on the shoulder of the highway. Recent statistics indicate that congestion delay due to freeway bottlenecks has increased dramatically in the last five years, and that the top ten urban areas incur 220 million hours of delay per year [1][1].

A freeway bottleneck is the critical roadway section at the leading edge of congestion with queues upstream and freely flowing traffic downstream. Recurring bottlenecks (those not caused by atypical conditions such as incidents) can occur for many reasons, including high volumes of entering and merging traffic, lane drops between ramps or at off ramps, weaving sections, and horizontal or vertical curves. Proper identification of freeway bottlenecks and their causes is the key to formulating plans for reducing congestion.

Major construction projects often address bottlenecks but these types of projects are expensive and take several years to plan, design, and construct. Relatively low-cost geometric and operational improvements (e.g., auxiliary lanes, ramp metering, truck restrictions) can often mitigate the effects of a bottleneck. The benefits of a low-cost improvement may not be as extensive or long-lasting as those of a major reconstruction project, but the improved system performance can easily justify its use.

Existing design and operations guides do not sufficiently address bottleneck sections. The AASHTO guide (Green Book) [2] is targeted to new construction. It provides design guidelines and standards, but is not oriented to the identification of bottleneck types, and low-cost solutions. The Highway Capacity Manual (HCM2010) [3] is oriented toward the analysis of bottlenecks, but not towards identifying them or seeking solutions (except by repetitive application of the tools to different solutions). The HCM2010 does not provide guidance for selecting among design options, much less low-cost solutions.

The latest edition of the Federal Highway Administration (FHWA) Freeway Management and Operations Handbook (FMOH) [4] includes a Chapter on roadway improvements that can be used to mitigate bottlenecks (Chapter 5). Examples include auxiliary lanes, restriping to provide additional (narrower) lanes, use of shoulders and interchange improvements. Other Chapters discuss operational and control improvements (e.g., ramp metering, managed lanes). The Handbook also discusses performance measures for freeway operational analysis, analysis tools and describes systems for archiving and processing real-time data. FMOH is a useful reference document for freeway operations staff but does not describe in a systematic and comprehensive way the process for bottleneck identification and the development and evaluation of low-cost improvements. Recently a bottleneck primer was published by FHWA [5], largely based on the research performed in this project.

Determining the best improvement for a particular bottleneck can be difficult. The freeway congestion due to a bottleneck can spread several miles upstream and impact the arterial street system. Improving a bottleneck may result in the congestion moving downstream to a new bottleneck that was not apparent previously, greatly reducing the expected benefits. There also may be multiple bottlenecks along a section

[1] References appear in the order listed in the text, and they are listed in the References section

of freeway, further complicating the cause and effect interrelationships of each. Analysis of the entire network may be necessary to accurately estimate the impacts of proposed improvements.

1.1 Research Objective

The objective of this project is to develop a technical guide for identifying existing and future recurring freeway bottlenecks and determining appropriate low-cost geometric and operational improvements to mitigate them.

1.2 Project Tasks

The project consists of the following nine tasks[2]:

Task 1. Literature review: Review the domestic and international literature on processes and analysis tools for identifying recurrent freeway bottlenecks and for determining appropriate low-cost geometric and operational improvements.

Task 2. State of Practice: Identify State Departments of Transportation (DOTs) and metropolitan planning organizations that have established procedures for identifying recurrent freeway bottlenecks and determining low-cost improvements. Interview operating agencies with promising procedures to identify strengths and weaknesses of their approach.

Task 3. Definition of Bottlenecks: Develop a working definition of freeway bottlenecks and describe their principal causes, characterize types of bottlenecks and low-cost geometric and operational improvements suitable for each type, and discuss how bottlenecks and low-cost improvements affect the operation of the freeway and arterial network.

Task 4. Framework for the Analysis of Freeway Bottlenecks: Develop a systematic framework for identifying bottlenecks and determining appropriate low-cost improvements. The framework should include feedback loops, if appropriate. Assess institutional issues that may arise from implementation of the framework.

Task 5: Preparation of Interim Report

Task 6. Process for Bottleneck Identification and Determination of Improvements: Develop and document a systematic process for identifying recurrent bottlenecks and determining appropriate low-cost geometric and operational improvements. The process description should show how it fits within a typical planning and project scoping process and identify candidate analysis tools and data needs for each step of the process. The process should be capable of using real-time and projected data.

Task 7. Assessment of Analysis Tools: Assess the suitability of the primary analysis tools identified in Task 6 for identifying recurrent bottlenecks, estimating their network-wide impacts, and projecting the benefits and service life of potential improvements. The assessment should include the resources, level of effort, and data required to use the tools.

Task 8. Technical Guide: Develop a technical guide that presents the process, illustrates its use through case studies, and aids the selection of analysis tools. The guide should discuss the composition of the project development team, the proper documentation of design exceptions, and other institutional issues associated with implementing the process.

Task 9. Final Report

[2] Source: NCHRP 3-83 Problem Statement

1.3 Organization of the Report

This document is the final report for the project documenting the work performed and presenting the major findings. Chapter 2 describes the findings from the literature review. Chapter 3 presents the findings from the interviews with 14 operating agencies. Chapter 4 describes the analysis framework including bottleneck definition and classification, low-cost improvements per bottleneck type, and the process for the application of analysis tools. Chapter 5 describes the four case studies and presents the major findings. Chapter 6 summarizes the major project findings in bottleneck identification, mitigation measures and assessment of analysis tools along with recommendations for future research .

Appendix A includes the interview guide. Appendix B is the technical guide for application of the research findings in real-world conditions.

CHAPTER 2
LITERATURE REVIEW

This Chapter presents the findings from the review of the literature on bottleneck analyses, and low cost geometric and operational improvements. The literature search was undertaken using the Transportation Research Board's (TRB) TRIS database, and other sources available at the Institute of Transportation Studies Library, University of California, Berkeley. Researchers and practitioners were also contacted to identify ongoing research and findings that are still unpublished.

2.1 Bottleneck Identification

A bottleneck is defined as a roadway section where the traffic demand exceeds the normal freeway capacity, resulting in formation of queues upstream of that location and free-flowing traffic downstream. The bottleneck is called "active" when traffic flow through the bottleneck is not affected by downstream restrictions (spillback from downstream bottlenecks). Recurrent bottlenecks occur on the same location and time periods of the day. Their behavior and characteristics are reproducible over many days. Typically the bottleneck remains active throughout the peak period(s). Traffic queues dissipate from the back as *traffic demand drops* below the available capacity. On the other hand, non-recurrent bottlenecks due to incidents generally have shorter duration, although some major incidents may last a long time. Non-recurrent bottlenecks are non-reproducible since incidents are random events and may occur anywhere in the freeway system. Furthermore, traffic queues dissipate from the front following the incident removal, i.e., when the *normal capacity is restored*.

A hidden bottleneck occurs when traffic demand is metered by an upstream bottleneck. It becomes active only when improvements to the upstream bottleneck are made, and the full traffic demand manifests itself at the hidden bottleneck location. Hidden bottlenecks can also become active if enough traffic demand enters the freeway at locations downstream. Similarly, downstream bottlenecks can prematurely introduce congestion upstream at upgrades and other bottlenecks not yet failing independently. Thus, an important concept to consider is the system-wide effect of bottleneck improvements, some of which may actually have adverse consequences on the system performance. Just like ramp-metering, mainline metering through bottlenecks may be manipulated in such a way to effectively manage the location and system-wide impacts of congested flow.

In the real-world, there are many freeway congestion patterns whose roots are difficult to identify. We may observe both recurrent and non-recurrent bottlenecks in proximity to each other. Furthermore, there may be hidden bottlenecks that are activated following improvements at an upstream location or often the impacts of a recurrent bottleneck may be masked because of upstream incident blockages. Sorting through these complex flow patterns requires expertise and experience in data processing, algorithms for analysis of real-time data, and modeling tools that consider both local and system-wide impacts.

Identification of the bottlenecks and their causes and impacts requires data on freeway operating conditions: freeway geometrics, traffic demand (typically, traffic counts at 15 minute intervals) and origin destination data. Also required are traffic performance data: average speed (travel time), lane densities, queue lengths, queue discharge rates, vehicle-miles of travel (VMT), and vehicle-hours of travel (VHT). The data are collected using manual techniques, e.g., floating cars, aerial photography, count measurements from video recordings, or can be obtained from freeway surveillance systems (loop detectors, radar, video) that provide real-time measurements on the quality and quantity of the traffic stream. The following sections describe the procedures for bottleneck identification based on manual data collection (conventional approaches) and real-time data (use of surveillance systems).

Conventional Approaches

Freeway congestion maps are typically constructed from speed/travel time studies using floating cars at 15 minute intervals. Figure 2.1 shows a congestion map for California DOT (Caltrans) District 3 in Sacramento, California. Congested segments are defined based on an average speed below 35 mph for a period of at least 15 minutes [6]. Such congestion maps can pinpoint the location of freeway bottlenecks. Inspection of this map indicates that bottlenecks are located at the downstream ends of the congested freeway segments. Hidden bottlenecks may exist at the freeway interchanges.

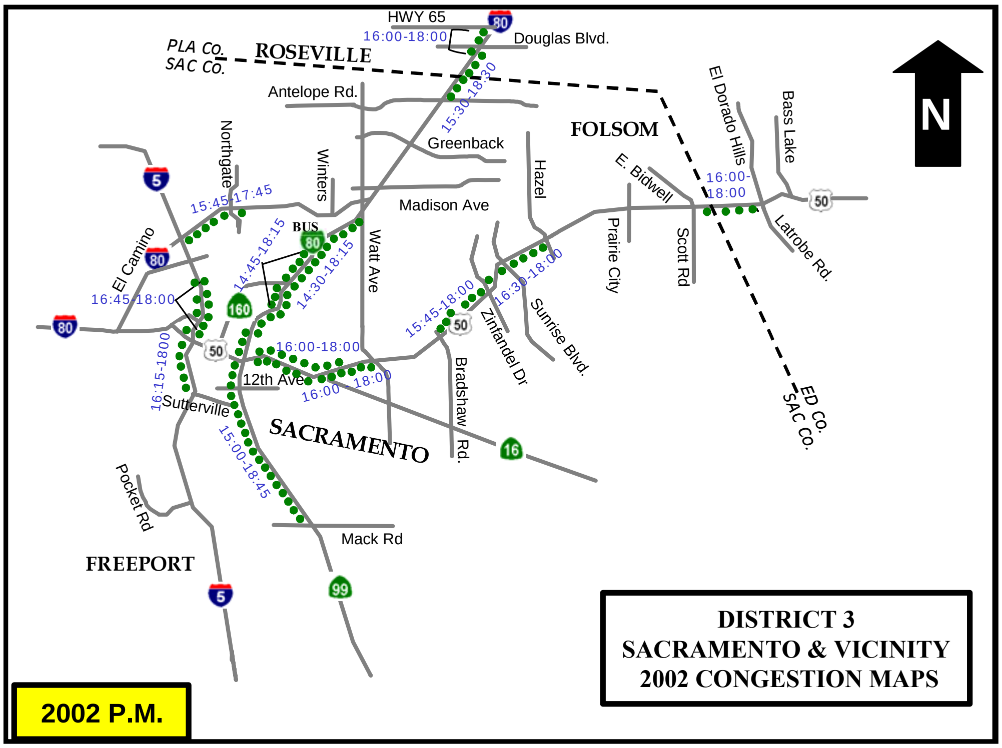


Figure 2.1 Sample Congestion Map

Figure 2.2 shows a schematic of a 19 mile section in the southbound direction of I-680 freeway in the San Francisco Bay Area. Figure 2.3 shows a contour plot of floating car speeds during the am peak period [7]. The numbered sections shown in the contour plot of Figure 2.3 correspond to freeway segments between on-and off-ramps starting from the Bernal Street on-ramp (Figure 2.2). Contour plots originally developed in freeway operations analyses in the early 60's [8] can be used to identify the bottleneck location(s) and the spatial and temporal extent of the congestion. In this example bottlenecks exist in sections 28 and 23, and they are associated with heavy on-ramp traffic and closely spaced on- and off-ramps without auxiliary lanes. Congestion starts at 5:45 am and lasts until 10:15 am (over 4 hrs). It is important to note that this method is not able to identify hidden, or interacting bottlenecks (in this example, possible bottlenecks could be on sections 19 and 21) since it strictly relies on real-time speed profile observations, which cannot be traced back to actual traffic demands. Density contour plots also can be constructed from aerial photographs of the study section taken at successive time intervals. The traffic demand at the bottleneck location can be estimated from density contour plots assuming a value for the density at capacity (optimum density) [9].

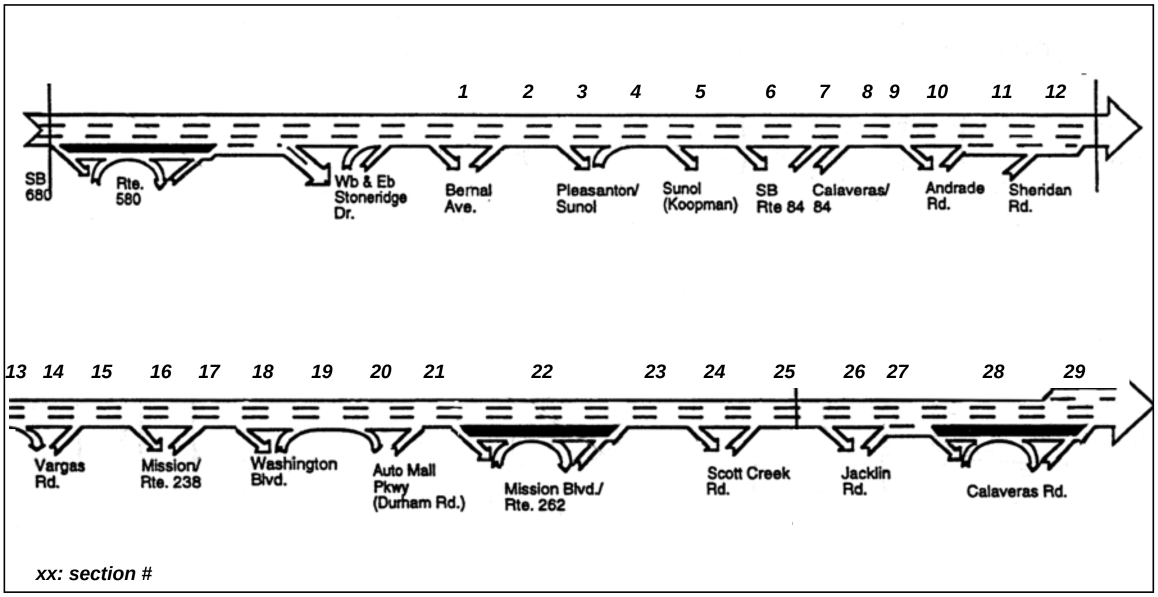


Figure 2.2 I-680 Freeway Southbound Direction

I-680 SB Tach Runs Speed Contour Plot

Interval	Section number																												
End	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
5:15																													
5:30	55	62	62	58	58	45	45	35	35																				
5:45	51	60	60	56	56	45	45	35	35	49	49	53	53	55	55	57	57	54	54	38	38	60	60	59	59	59	59	58	61
6:00	51	58	58	25	25	17	17	36	36	50	50	54	54	19	19	15	15	37	37	35	35	52	52	59	59	59	61	58	61
6:15	65	64	64	16	16	13	13	25	25	30	30	35	35	19	19	15	15	20	20	31	31	55	55	59	59	59	59	57	62
6:30	57	63	63	16	16	10	10	14	14	11	11	17	17	18	18	15	15	18	18	30	30	51	51	59	59	59	58	54	61
6:45	57	63	63	15	15	9	9	15	15	11	11	17	17	16	16	14	14	17	17	29	29	47	47	59	59	59	53	45	61
7:00	57	64	64	15	15	8	8	15	15	10	10	15	15	17	17	11	11	18	18	29	29	43	43	59	59	59	43	36	61
7:15	61	63	63	14	14	8	8	19	19	8	8	11	11	14	14	11	11	18	18	31	31	37	37	56	56	56	35	33	61
7:30	59	63	63	15	15	15	15	10	10	10	10	7	7	18	18	11	11	18	18	33	33	33	33	56	56	56	28	33	61
7:45	50	65	65	20	20	12	12	13	13	9	9	7	7	18	18	12	12	17	17	33	33	28	28	29	29	29	33	34	61
8:00	50	65	65	22	22	10	10	13	13	9	9	13	13	12	12	11	11	17	17	19	19	31	31	42	42	42	29	33	61
8:15	46	64	64	22	22	10	10	13	13	9	9	9	9	12	12	13	13	18	18	39	39	26	26	42	42	42	29	34	61
8:30	42	64	64	49	49	14	14	13	13	9	9	12	12	12	12	15	15	19	19	23	23	33	33	61	61	61	29	33	61
8:45	58	63	63	56	56	14	14	13	13	8	8	16	16	21	21	10	10	21	21	23	23	40	40	56	56	56	28	33	61
9:00	55	59	59	64	64	18	18	15	15	12	12	20	20	18	18	10	10	21	21	35	35	45	45	60	60	60	30	34	61
9:15	56	58	58	60	60	22	22	17	17	13	13	14	14	17	17	32	32	26	26	34	34	53	53	60	60	60	30	33	61
9:30	57	56	56	60	60	42	42	19	19	17	17	14	14	16	16	30	30	29	29	35	35	53	53	60	60	60	28	34	61
9:45	57	64	64	63	63	62	62	21	21	22	22	15	15	23	23	34	34	35	35	36	36	57	57	61	61	61	29	33	61
10:00	57	63	63	63	63	62	62	42	42	22	22	15	15	30	30	37	37	40	40	38	38	61	61	58	58	58	39	35	60
10:15	57	63	63	63	63	63	63	63	63	63	63	63	63	51	51	44	44	33	33	46	46	59	59	55	55	55	55	48	60

Figure 2.3 I-680 Speed Contour Plot Based on Floating Car Data

The speed contour plot shown in Figure 2.3 represents only a single day's worth of data. So it is difficult to determine which bottlenecks are recurrent and which ones are transitory, incident-related problems. Also it is difficult to determine the impacts of bottlenecks based on a single day of data. Figure 2.4 shows the average travel times vs. time of day for the I-680 test section collected from floating car runs on three successive weekdays. Note that the differences in travel times could be quite high due to variations in traffic demand or due to the presence of incidents. Also, the variability is higher during the times of congestion build-up (6:00 to 8:00 am). These sample results illustrate that data from several incident-free days are needed to reliably identify the bottleneck location and assess its impacts.

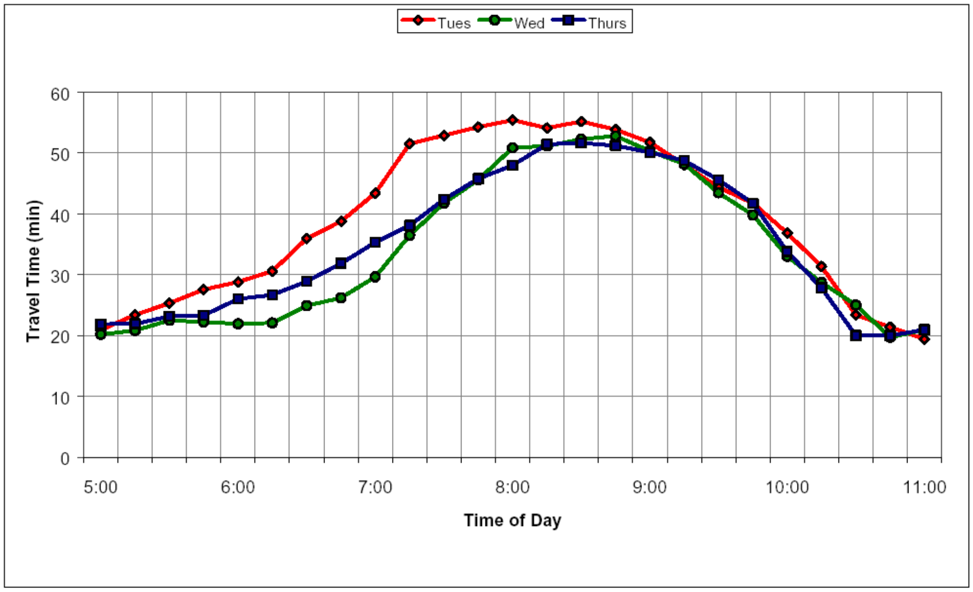


Figure 2.4 Variability of Travel Times—I-680 SB Test Section

Use of Surveillance Data

Surveillance systems (loop detectors, radar, video) provide real-time vehicle count and occupancy data for each freeway lane at 20 or 30 second intervals. Count is the number of vehicles crossing the detector over the data collection interval (20 or 30 sec). Occupancy is defined as the proportion of time the detector is occupied over the data collection interval, and is a surrogate measure for density. Occupancy values below 10% indicate free-flow conditions, whereas values approaching 100% indicate stopped traffic (jam density). Vehicle speeds are calculated from flow and occupancy data assuming an “effective” vehicle length (often called g-factor), i.e., the average length of the vehicle plus the detector length. Speeds can also be measured directly from two closely-spaced detectors (e.g., double loops –speed traps). The raw data are transmitted to a Transportation management Center (TMC) where they are checked for accuracy through diagnostic tests, and then aggregated to produce average speeds, flows and densities for 5 min, 15 min or hourly time periods.

Time-series plots of real-time occupancy (or speed) data at successive loop detector pairs can pinpoint the bottleneck location. The bottleneck is located in the freeway section with high occupancy (density) values upstream of the bottleneck, and associated low flows and speeds, while downstream of the bottleneck high speeds and low occupancies are observed. Figure 2.5 shows a time-series plot of 5 minute occupancy values between successive loop detectors along a section of I-880 freeway in San Francisco Bay Area. It can be seen that the occupancy at the upstream detector (labeled LP 400682) located at postmile 39.33 significantly increases at time 7:30 am indicating the onset of congestion. The downstream detector LP 400983 located at postmile 39.98 (approximately 0.6 m) downstream maintains a low occupancy. This indicates that a bottleneck exists between the two stations, and remains active for about two hours (from 7:30 to 9:30 am). Contour plots of speeds or occupancies from detector data can also be used to identify bottlenecks. Figure 2.6 shows a contour plot of vehicle speeds on the same freeway section for the am peak period (6:00-10:00 am). The plot confirms the presence of a bottleneck at the same location as in Figure 2.5, but also shows that a second bottleneck exists at postmile 26. The plot can also used to observe both the spatial and temporal impacts of each bottleneck.

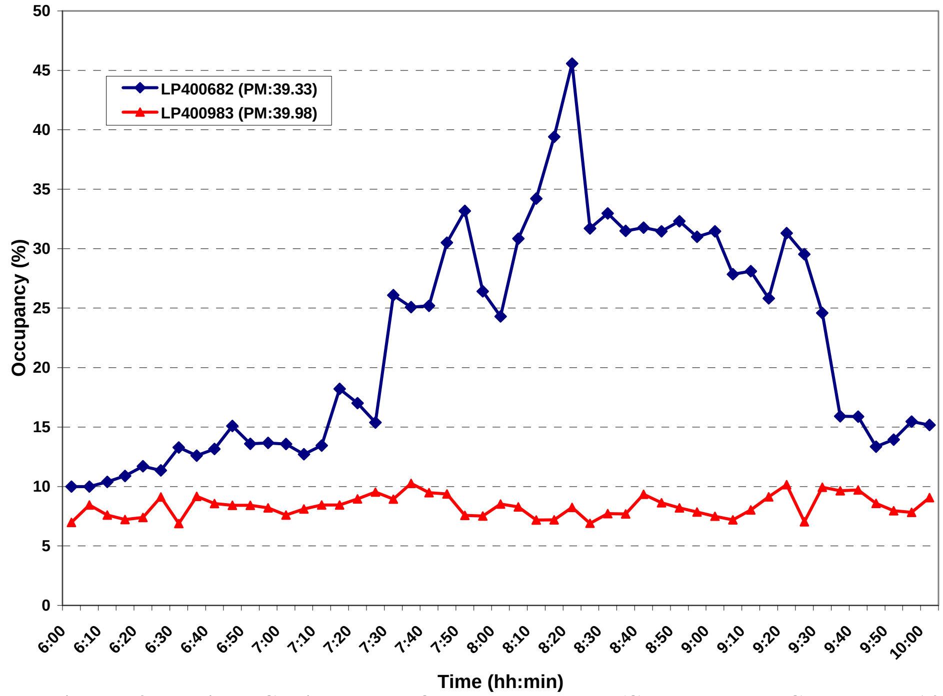


Figure 2.5 Time-Series Plot of Detector Data (Source: PeMS system [10])

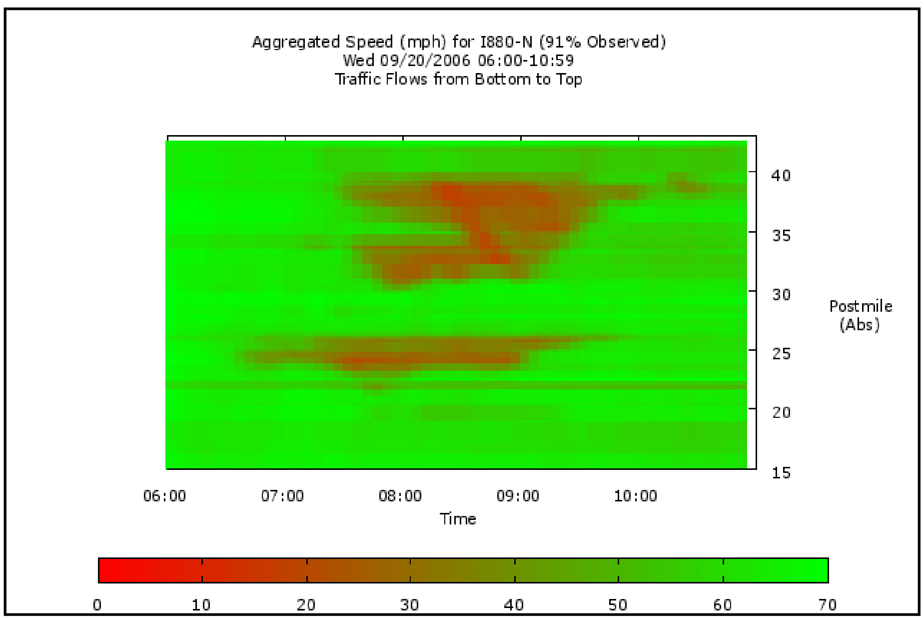


Figure 2.6 Speed Contour Plot from Detector Data (Source: PeMS system [10])

Figure 2.7 shows a speed-distance plot on the same freeway section derived from the detector data that can be used to assist in bottleneck identification. Note the location of the bottlenecks near postmiles 26 and 39 as already shown in the contour plot (Figure 2.6), and the time-series plot in Figure 2.5 (for the bottleneck in postmile 39). As it was discussed previously such speed profiles could have derived from floating car data, which is more expensive, statistically less reliable and more time-consuming than the use of real-time data. Manual studies can only be undertaken for a few days due to the high cost and effort required [11,12]. On the other hand, real-time data are continually available and can be readily used to analyze bottleneck and congestion patterns over time, provided that the detector data are valid and the detector stations are closely spaced. Manual data collection may be cost-effective if a surveillance system does not exist.

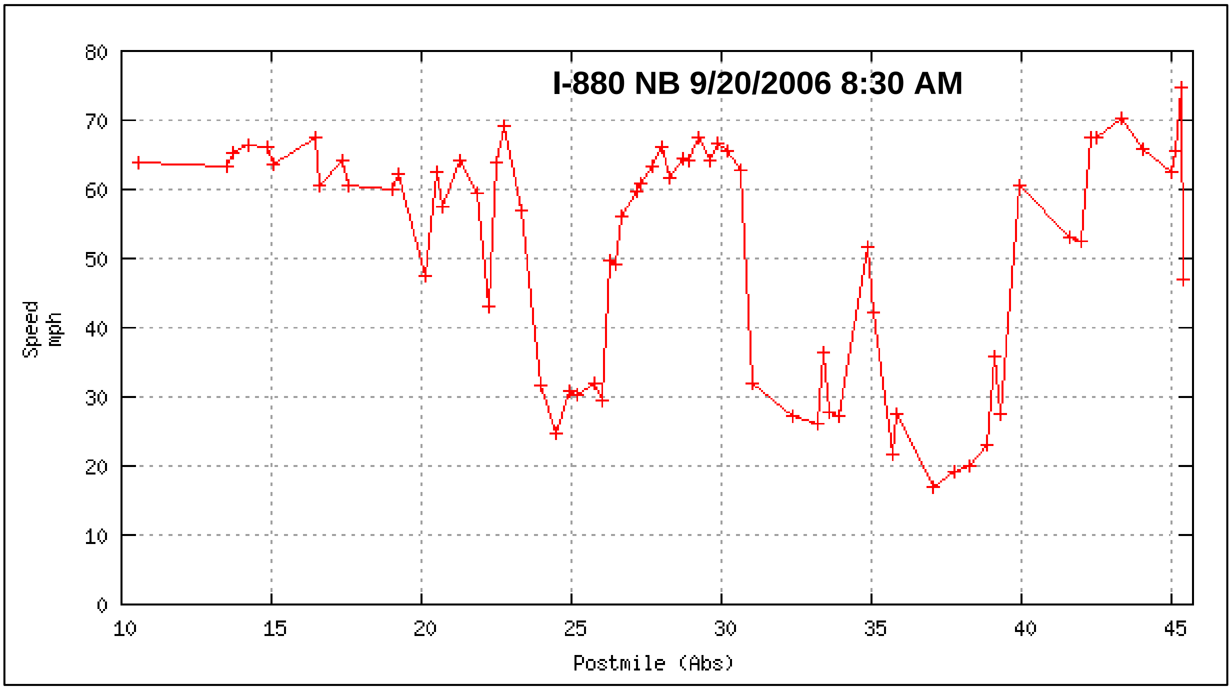


Figure 2.7 Speed-Distance Plot from Detector Data (Source: PeMS system [10])

Zhang and Levinson [13] used the occupancy values from successive loop detectors to identify bottlenecks in the Twin Cities metro area in Minnesota. They found that when the minimum 30 sec occupancy value at a detector station across all lanes is larger than 25%, the traffic is in the congested region; if the maximum occupancy value is less than 20% then the traffic is free-flowing. These occupancy values are typical of occupancy thresholds between congested and uncongested conditions. If the upstream station of a freeway segment is congested and the downstream station is uncongested for more than 5 minutes, a breakdown has just occurred and the segment is considered an active bottleneck. A total of 27 bottlenecks were identified in the entire freeway system in the pm peak period from the analysis of data from over 4,000 detectors.

Ruphail and al [14,15] analyzed volume, occupancy and derived speed detector data from an 11-mile section facility of I-5 in Seattle, WA during the peak periods from June to August 1996 to develop a congestion prediction algorithm of freeway breakdown. Speed was found to be the best predictor of breakdown using a 5 minute prediction horizon. Specifically mean speed, minimum speed and speed change rate were the best explanatory variables for congestion prediction. Directional peak algorithms produced a correct prediction rate of nearly 75%, but a slightly high false alarm rate of 11%. Overall, algorithms based on 1 minute data performed better than 5 minute data, and short term algorithms (based on 5 minute prediction horizon) performed better than longer term algorithms. The data also clearly distinguish between recurrent and non-recurrent bottlenecks based on observations of detector data over an extended period of time on similar weekdays and hours.

Several researchers have used cumulative curves of vehicle count ("N curves") and occupancy data vs. time to identify and characterize freeway bottlenecks [16,17,18,19]. Cumulative curves of flow vs. time are constructed at each detector station. The original N curves are shifted horizontally by the average free-flow trip time from their respective locations to the most downstream detector location. Any vertical differences between the curves indicate excess vehicle accumulations. Each N curve is further rescaled by subtracting a "background count" (corresponding to the average flow rate) to better visualize the excess accumulations. Such excess accumulations indicate bottleneck activation. The maximum flow rate before the bottleneck activation, and the queue discharge rate can be determined from the slope of the cumulative N curves.

Recently, an algorithm was developed to automatically identify bottlenecks in a freeway system using real-time data from loop detectors [20]. The algorithm uses the difference of vehicle speeds at each detector and the detector immediately downstream, plus additional criteria to the duration of activation time and detector location to differentiate between recurrent and non-recurrent (incident related) bottlenecks. The algorithm is described in detail in Section 4.5 of this report. The algorithm was applied to the freeways in San Diego and Sacramento regions in California (a total of 581 directional freeway miles with over 1,100 detector stations), using the detector data from the California's Freeway Performance Measurement System (PeMS) [10,11,21,22]. The PeMS system processes 2 GB/day of 30-second data from over 30,000 loop detectors in real time to produce traffic performance measures. PeMS includes numerous plots and other visualization tools to facilitate data analysis for managers, engineers and planners.

2.2 Bottleneck Classification and Characteristics

The project focuses on recurrent freeway bottlenecks, which occur wherever there is either a surge in demand or a restriction in the capacity. Demand surges occur at on-ramps and merges. Solutions to these types of bottlenecks generally consist of downstream capacity enhancements and upstream demand metering. Capacity restrictions occur where the freeway geometry changes (lane drops, grade increases, narrowing of lanes and shoulders, curves, tunnels, bridges, etc). Solutions to capacity restrictions type of bottlenecks consist of capacity enhancements in the bottleneck section. Metering of upstream demand may also be feasible if eligible metering points can be identified. Some of the geometric features that contribute to the occurrence of freeway bottlenecks include:

- On-ramps sections with no auxiliary lane additions, or with short acceleration lanes
- Weaving sections, particularly out of dropped lanes
- Lane drops on basic freeway segments, or following an off-ramp
- Tunnel sections, where the free-flow speeds (FFS) may be reduced and may introduce driver visibility transition issues
- Horizontal curves where vehicle paths may cross into the next lane
- Upgrades, particularly in the presence of heavy vehicles
- Narrow lanes on older freeways
- Lateral obstructions which reduce FFS, particularly on bridge sections

Several studies have investigated the association of the pattern of the flow breakdown and bottleneck type. Empirical findings on on-ramp merge bottlenecks indicate that merge bottlenecks are activated when the density on the outer (shoulder) freeway lane exceeds a threshold value [23]. Another field experiment reported that flow breakdown occurs first on the freeway median lane at freeway lane drops [19].

Extensive work on bottleneck formation and characteristics on freeway sags and tunnel entrances has been undertaken in Japan. The findings from numerous studies have been summarized by Koshi [24]. The capacity before breakdown is about 1,500 vphl for two lane sections, dropping to 1,200-1,350 vphl when the queue is formed (a reduction in discharge flow of about 15%). The following mechanism of breakdown was observed: drivers do not notice the gradual reduction in their speeds with the increase of the grade at the sag, and try to keep their following distances with the cars ahead, which results in a slight flow reduction. When a long platoon of vehicles passes though the sag, the flow reduction accumulates toward the tail of the platoon which results in stopped vehicles in tail of the platoon and queue formation. In a recent study in Germany on freeway upgrades [25], it was found that traffic breakdowns due to the upgrades in all five study sections occur at the beginning of the upgrade, usually on the first 500 m (1500 ft). The section capacities were not affected by the length of the upgrade.

Freeway bottlenecks may also occur when queues on freeway off-ramps spillback onto the freeway mainline [26,27]. This may be because of heavy traffic off-ramp traffic and insufficient capacity at the downstream end of the off-ramp (e.g., short green time at the traffic signal controlling the off-ramp traffic). Field observations indicate that even if the queues of exiting vehicles are in the right-most auxiliary lane, the capacity of the freeway is reduced because drivers reduce their speeds when they see the queues of exiting vehicles.

Findings from empirical studies indicate that following the bottleneck activation, the resulting queue discharge flow rate drops below the maximum flow rate observed under free-flow conditions. This “capacity drop” ranges from 3 to 15 percent of the maximum flow (capacity) before the flow breakdown, and depends on the freeway geometrics and can vary on different days [28,29,30,31]. In the Minnesota study described above [13], the drop in the flow following the bottleneck activation ranged from 2% to 11% with a mean of 5.4% and a median of 4.9%. The study also found that the daily averages queue discharge flows at each bottleneck are normally distributed. Another study reported a significant variation in queue discharge rates at bottlenecks [32]. There is no consensus on the reason of the capacity drop. It may be related to the traffic friction upstream of the bottleneck or the lower acceleration of vehicles in high density areas.

2.3 Bottleneck Mitigation Measures

A number of geometric and operational improvements for recurring bottlenecks have been proposed and implemented. As it was mentioned earlier the FHWA’s Freeway management and Operations Handbook [4] and the Bottleneck Primer [5] include recommendations on roadway and operational improvements. Also, bottleneck mitigation measures are described in the ITE guide “A Toolbox for Alleviating Traffic Congestion” [33]. Walters et al [34] summarized the results of several case studies in Texas [35,36] where minor geometric and operational improvements to bottleneck sections on freeways have yielded considerable benefits in terms of speed, volumes and crash history. The improvements included converting the outside shoulder to an auxiliary lane, re-striping a one-lane ramp to two lanes, closing an entrance ramp, among other options. The improvement costs varied from $8,000 to $2.45 million, and the resulting Benefit/Cost ratios ranged from 9:1 to 400:1. Machemehl et al [37] proposed a series of freeway operational flexibility concepts, some of which are targeted to removing or mitigating the effects of bottlenecks, such as auxiliary lanes, and provision of shoulders at lane drops and weaving sections.

Ramp metering is the most widely used operational improvement measure. Several ramp metering studies have reported benefits in reducing freeway congestion. The recently published “Ramp Management and Control Handbook” [38] describes in detail various ramp metering strategies, and other ramp treatments including ramp closures. The design of a particular ramp metering scheme should maximize the outflow from the merge bottleneck, i.e, avoid the capacity drop [39], and should carefully consider the impacts on the ramps and the adjacent arterial street networks. Recent research has developed algorithms for ramp queue control which at the same time provide effective metering [40].

A listing of mitigation measures from the review of the literature is given below:

Geometric:

- Auxiliary lanes connecting short segments (1/4 mile) of on and off ramps
- Removal of freeway weaving from the mainline to parallel CD road
- Provision of 2,500 ft of paved shoulder at lane drops
- Provision of a 12 ft paved left shoulder 1,500 upstream and downstream of weaving sections
- Added full shoulder near bottlenecks
- Re-striping to add narrower lanes within the same right of way (ROW)
- Reversible or contra flow lanes (taken out from the non-peak direction)
- Connection of frontage road discontinuities to enable trips to bypass the "last" bottleneck entrance ramp

Operational:

- Truck-lane restrictions
- Truck-only lanes
- Ramp metering
- Temporary on-ramp or off ramp closures during peak hours
- Traveler information to divert traffic to parallel facilities upstream of a bottleneck
- Re-striping HOV lane within existing ROW (no new construction)

In Europe, most notably in Germany and Netherlands, research and implementation activities are concerned with dynamic capacity enhancements at bottleneck locations using intelligent transportation systems (ITS) technologies [41,42]. Examples include use of the right shoulder (peak lane) or adding a narrow lane on the left (plus lane). The added "lanes" are displayed to the drivers via changeable message signs (overhead arrows) and they are continually monitored via video cameras from the TMC. Figure 2.8 below illustrates an example of dynamic cross section applications in Netherlands [43]. Field evaluations indicate that the dynamic added lanes increase capacity by about 40-50% (about half of a full lane), are effective in alleviating bottlenecks, with no adverse safety impacts.

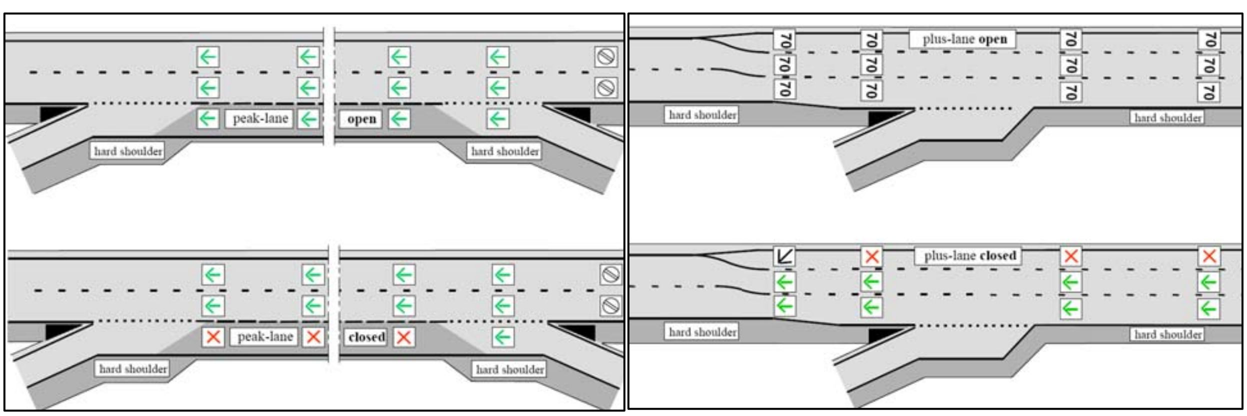


Figure 2.8 Peak Lane and Plus-Lane Design (Source: Stembord at al [43])

Other ITS related bottleneck mitigations in Europe include use of dynamic speed limits on freeways [44,45]. The objective is to reduce the difference of vehicle speeds on the freeway mainline, create smoother traffic flows and reduce the probability of flow breakdown. The implementation of dynamic speed limits on German autobahns reduced the probability of flow breakdown by a factor of 3, based on the analysis of detector data. Other studies reported reductions in the number and severity of freeway accidents. No systematic improvements on the queue discharge rates at bottlenecks have been reported. It should be noted that dynamic speed limits are enforceable in Europe; USA generally lacks enforcement provisions for successful applications.

The implementation of bottleneck improvements should carefully consider the impacts to the entire freeway system under study. As it was already mentioned, removal of a bottleneck may create another bottleneck elsewhere on the freeway (hidden bottlenecks). Hidden bottlenecks exist at freeway locations where the traffic demand exceeds the available capacity, but the demand cannot reach the hidden bottleneck location because of the presence of upstream or downstream primary bottleneck(s). Hidden bottlenecks cannot be identified in the field; careful analysis of the freeway system is needed. In a number of cases primary bottlenecks "meter" the traffic downstream and prevent system breakdown. Yagar and Hui [46] evaluated a number of bottleneck improvements on a section of Highway 401 in Toronto and found that about half of the proposed improvements to the active bottlenecks had a net negative effect to the system because of the activation of the hidden bottlenecks.

The regional bottleneck study undertaken by the Maricopa Association of Governments in Arizona [47] provides an example of taking into consideration system-wide impacts in the analysis of bottleneck mitigation measures. In this study, a systematic inventory of the operating conditions of the regional freeway system was performed to identify bottleneck locations and analyzed improvement measures through simulation modeling. Proposed mitigations included adding auxiliary lanes, constructing collector-distributor roads. On two locations, it was found that the proposed improvements would result in reaching quicker the congested central Phoenix area, thus worsening the congestion problem; no improvements were recommended on those locations; these bottlenecks serve to meter traffic approaching the central Phoenix area.

Caltrans recently developed a systematic process for conducting corridor management planning (CMP) studies [48]. The process includes procedures for defining the study corridor (freeway and adjacent surface street network), data collection, estimation of performance measures, identification of problem locations, development and evaluation of design and operational improvements and institutional issues.

2.4 Analysis Techniques

The identification of bottlenecks and the evaluation of the low-cost bottleneck improvements require analysis tools to quantify the impacts of existing as well as *projected* bottlenecks, and the expected benefits in terms of reductions in delay and queue lengths, increase in throughput and other measures of effectiveness (MOEs). The analysis tools include algorithms to process real-time data and/or analytical and simulation models. The tools for bottleneck analysis must satisfy the following requirements:

- model the bottleneck impacts (queue formation and dissipation) in time and space
- model the bottleneck impacts on the upstream and downstream sections over time
- model the freeway system so it can address the issue of hidden bottlenecks
- model the proposed low-cost solutions
- require data that are commonly available from State DOTs and MPOs
- fit into existing planning processes (e.g., Highway Capacity Manual analyses)

Existing modeling tools can be classified into four major categories: sketch planning tools, travel demand models, analytical deterministic techniques (e.g., HCM2010) and simulation models [49]. The choice of the particular tool depends on the several criteria including analysis context, size of the study area, facility types to be modeled, travel modes to be included in the analysis, types of management strategies to be evaluated, performance measures to be estimated, traveler responses to be analyzed and overall tool cost-effectiveness.

Sketch-planning methodologies use simplified analytical relationships and aggregated data to produce approximate estimates of travel demand and transportation performance measures for preliminary analysis of transportation improvements. These techniques can provide approximate estimates of bottleneck congestion impacts [50], but they are not suited for detailed bottleneck analyses.

Travel demand models (often called four-step models) simulate the trip making behavior into four sequential steps: trip generation, trip distribution, mode choice and traffic assignment. Travel demand models produce estimates for link volumes and average speeds for each link of the network. The estimated speeds however are not accurate for traffic operations analysis or evaluation of traffic management strategies (in terms of speed, delay and queues) because the traffic assignment step in the four-step models does not take into account the presence of bottlenecks and the queue formation and dissipation queuing on the network links. Planning models can be used to obtain future traffic demands at bottlenecks for inputs to detailed operational analyses [51].

Analytical/Deterministic Tools (HCM): Analytical deterministic tools consist of analytical relationships between traffic demand and network characteristics (supply). These techniques are suited for analyzing impacts at an isolated location, e.g., the queuing diagram to estimate delay and queue length at a freeway bottleneck or delay at a signalized intersection approach [52,53]. HCM2010 [3] includes the most widely used analytical & deterministic methodologies to estimate the capacity and Level of Service (LOS) based on performance measures for each facility type, e.g., density for basic freeway segments.

The HCM2010 procedures are macroscopic (consider average traffic stream characteristics), deterministic (ignore stochastic variability), and static (analyze operating conditions for a fixed-time analysis period and ignore transitions in traffic conditions). The HCM procedures are ideal for analyzing the performance of isolated facilities with relatively moderate congestion problems, but they cannot generally evaluate system effects, e.g., it is assumed that the performance of the segment under study is not adversely affected by conditions on the adjacent roadway. Furthermore, they are not well suited in analyzing freeway management strategies (e.g., ramp metering, traveler information systems).

FREEVAL is a macroscopic analysis tool developed North Carolina State University to implement the analysis procedures in Chapter 10 (Freeway Facilities) first introduced in HCM2000 [54]. Because HCM procedures do not deal with congested freeway conditions, FREEVAL uses the HCM2000 speed-flow curve and shock-wave analysis to deal with oversaturation [55]. FREEVAL uses the abilities of Microsoft® Excel and the Visual Basic programming language to create a simple to use model in spreadsheet format. The model has been updated with the analysis procedures in the 2010 edition of HCM.

Simulation models

Simulation tools model the traffic stream movements and interactions in time and space [49,56,57,58]. They can model the build up, propagation and dissipation of traffic congestion, transitions in traffic states, plus local and system-wide impacts of operating conditions and mitigations. They provide several performance measures per vehicle trip (travel time, delay, number of stops), network link (throughput, average speed, queue length) and the total system. Existing simulation models are listed in FHWA's "Traffic Analysis Toolbox Volume II: Decision Support Methodology for Selecting Traffic Analysis Tools," [49], and are classified in the following categories:

Macroscopic models are based on the conservation of flow and deterministic relationships of the flow, speed, and density of the traffic stream. They consider flow rates or platoons of vehicles and simulate traffic flow in small time increments on each section of the network. Macroscopic models that can analyze bottlenecks and their system-wide impacts include FREQ developed at the University of California, Berkeley, KRONOS, developed at the University of Minnesota, FREFLO (CORFLO) developed for FHWA, and METACOR and METANET models developed in Europe to analyze ramp metering strategies in Europe. FREQ is the most widely used model for freeway operations studies and development of ramp metering plans and has been used in a number of bottleneck specific analyses by Caltrans Districts and elsewhere (e.g., the Arizona regional freeway bottleneck study [47]).

Mesoscopic models simulate individual vehicles, but their movements and interactions are modeled based on macroscopic traffic flow relationships, i.e., they combine the properties of both micro and macro simulation models (e.g., the DYNASMART-P model). Mesoscopic models are mostly suited for modeling diversion strategies and traveler information systems.

Microscopic models simulate the movement of individual vehicles based on car-following, lane-changing and queue discharge algorithms every one second (or a fraction of a second). Microscopic models can model in detail the effect of design, control and management scenarios but require additional input data and significantly higher computer time and storage requirements compared to macroscopic models. Several microscopic simulation models are available for modeling the operation of a freeway system, most notably CORSIM, INTEGRATION, AIMSUN2, PARAMICS, VISSIM and WATSIM.

Microsimulation models are increasingly being used in the analysis of freeway corridors. The advantage of these models is that they can model in detail alternative designs and control schemes and provide graphical displays and animation so the users (and decision makers) can better understand existing operations and the effectiveness of proposed mitigation measures. However, they require a large amount of input data and several parameters that must be calibrated to local conditions [59]. It is also important to recognize that none of these models accept capacity as an input. Rather, capacity is a derived outcome of the car-following and lane changing algorithms that are imbedded in each model. Typically, the user may have to overload a link on the network and observe in the output, the maximum output flow on the link to determine its capacity. The derived capacity may be adjusted by changing certain model parameters (e.g. the target headway and reaction time), but the number of calibration parameters can be very large, and their effect on each other and on freeway segment capacity is largely unknown.

CHAPTER 3
STATE OF PRACTICE

This Chapter presents a description and critique of procedures followed by operating agencies to identify bottlenecks and to develop and evaluate low-cost improvements. The original scope of work called for interviewing four to six operating agencies to identify and document their strengths and weaknesses of their approach for bottleneck identification and mitigation. It was decided to expand the task and interview more agencies to obtain a representative range of operating conditions and approaches across the country, as well as overseas. The following criteria were used for agency selection:

Size and characteristics of the freeway system: Operating agencies in charge of an extensive freeway system that is congested most of the day with numerous and interacting bottleneck locations may have different procedures than small to medium size agencies that have to deal with operational problems on isolated locations during the peak periods.

Use of performance measures: Some of the agencies should have established performance measures in freeway operational analysis to identify bottlenecks and assess the effectiveness of improvements. Bottleneck related performance measures include throughput (discharge volume), queue length (miles), delay (veh-hrs), and extent of the congestion (hrs).

Use of modeling tools: Operating agencies use a variety of analysis tools ranging from simple queuing diagrams on isolated bottleneck locations to complex simulation models on freeway corridors. There is a wide range in the capabilities of existing analysis tools as well as in data and level of effort required for their application.

Use of real-time data: Some of the agencies should have freeway TMCs in place and experience with the archiving and use of real-time data for freeway operational analysis.

An interview protocol was developed (included in Appendix A). Questions were related to data and analysis procedures for bottleneck identification and development of mitigation measures, as well as to agency characteristics (annual budget, staffing, institutional arrangements, agency policies, legislative mandates and policies, etc.) to help understand the processes followed by the agency in bottleneck related studies. We also gathered background information on the general design characteristics and congestion level and patterns of the freeway system in each area, and data on specific bottleneck improvement studies, including benefits and costs of bottleneck mitigations.

The interviews were conducted with key operations staff to obtain specific information on the bottleneck analyses undertaken by the agency and solicit materials for possible case studies. We did also interview planning staff to gather information on how the specific studies fit on the agency's overall planning and programming of transportation improvements.

A total of fourteen interviews have been completed for this project. Eight interviews were conducted with staff from State DOTs:

Arizona DOT
California DOT (Caltrans, District 4, San Francisco Bay Area)
Missouri DOT
Nevada DOT
North Carolina DOT
Pennsylvania DOT
Washington DOT
Wisconsin DOT

two interviews were conducted with planning organizations:

Metropolitan Transportation Commission for the San Francisco Bay Area (MTC)
Illinois Tollway Authority

and four interviews were conducted with European transportation agencies in

Denmark (Danish Road Directorate)
Germany (Ministry for Building and Transport, Northrine-Westphalia)
Greece (Attica Tollway Operations & Maintenance Company)
Netherlands (Department of Transport)

Once these interviews were completed and analyzed, follow-up interviews ware conducted with the following four agencies focusing on the approaches being used to fund bottleneck improvements:

Puget Sound Regional Council for the Seattle, Washington metropolitan area
California DOT (Caltrans, District 7, Los Angeles)
Florida Department of Transportation
Maryland State Highway Administration

The following sections present the main findings from the interviews with the operating agencies. Detailed transcripts of each interview have been compiled and are available upon request.

3.1 Size and Characteristics of the Agencies' Systems

Table 3.1 shows the interviewed agencies according to the total freeway lane-miles in their system, the total freeway annual vehicle-miles traveled (VMT), and the number of freeway bottlenecks each interviewed agency have identified in their system. Annual VMT on the interviewed agencies' freeway networks range from 700 million to 62.5 billion with an average of 18.4 billion. The number of identified bottlenecks in each interviewed agency's system ranged from two to 84 with an average of 27. However, the number of bottlenecks varies not only according to the size and amount of traffic on each system, but according to the resources each agency has spent and the definitions used to identify them.

Table 3.1 Size and Characteristics of the Interviewed Agencies' Systems

	Interviewed Agency	*Freeway Lane-Miles*	*Freeway VMT (Billions)*	*# of Freeeway Bottlenecks Identified*
1)	Washington DOT Northwest Region	1,679	N/D	10 [3]
2)	Arizona DOT Valley Transportation Group (Phoenix Metro Area)	1,634	N/D	14
3)	Caltrans District 4	2,047	30.5	84
4)	Metropolitan Transportation Commission	2,047	30.5	84
5)	Nevada DOT	164	4.4	4
6)	North Carolina DOT	5,000	18.7	5
7)	Missouri Department of Transportation	1,300	0.7 [2]	20
8)	Illinois Tollway Authority	274	8.5 [1]	10
9)	Danish Road Directorate (DRD)	2,650	6.8	19
10)	The Netherlands: Ministry of Transport, Public Works and Water Management	6,000	10.3 [1]	50 [3]
11)	Wisconsin DOT	N/D	62.5	N/D
12)	Germany: Ministry for Building and Transport, Northrine-Westphalia	1,398	N/D	20
13)	Pennsylvania Department of Transportation	8,878	28.2	N/D
14)	Greece: Attica Tollway Operations & Maintenance Company	218	0.9	2

Legend
N/D = No data available.
1 = Estimated based on daily VMT data provided.
2 = Total Highway VMT.
3 = The number of bottlenecks identified so far.

3.2 Definition of Freeway Bottlenecks

The way that a freeway operations and management agency defines a bottleneck can help us understand how they measure, analyze, and try to improve them. Interviewees were asked: “Does your jurisdiction have an operational definition of a recurrent freeway bottleneck? (If yes, what is it?)”. Table 3.2 summarizes the responses to this question and provides an indication of whether or not the definition used is a formal one or if it is a more informal or “working” definition.

Ten of the 14 interview participants responded that they had either formal or working definitions. Two of these nine have working definitions that are not quantitatively based, but rely more on qualitative assessments of traffic conditions to determine bottleneck locations. Of the three general categories of bottleneck definitions – volume/capacity, speed and qualitative – those based on speed were the most frequently reported, with five of the interviewed agencies reporting they have definitions based on this measure. Typically, those agencies using speed measures also have more formalized definitions. However, the speed thresholds differ from agency to agency. While the Greek Attica Tollway & Operations Company uses free-flow speed as the threshold, the Northwest Region of the Washington DOT and Caltrans District 4 both use more conservative thresholds of 45 and 35 mph respectively. The Netherlands Ministry of Transport uses 19 mph (30 kph) because this (in their experience) is the speed at which a queue will start to form.

Table 3.2 Freeway Bottleneck Definitions Used by Interviewed Agencies

	Agency	*Volume/Capacity*	*Speed*	*Qualitative*
1)	Washington DOT Northwest Region	1	5	1
2)	Arizona DOT Valley Transportation Group (Phoenix Metro Area)	1	3	1
3)	Caltrans District 4	1	5	1
4)	Metropolitan Transportation Commission	1	1	1
5)	Nevada DOT	1	1	1
6)	North Carolina DOT	N/D	N/D	N/D
7)	Missouri Department of Transportation	1	1	3
8)	Illinois Tollway Authority	N/D	N/D	N/D
9)	Danish Road Directorate (DRD)	5	1	1
10)	The Netherlands: Ministry of Transport, Public Works and Water Management	1	5	1
11)	Wisconsin DOT	1	1	5
12)	Germany: Ministry for Building and Transport, Northrine-Westphalia	3	1	1
13)	Pennsylvania Department of Transportation	3	1	1
14)	Greece: Attica Tollway Operations & Maintenance Company	1	5	1

Definitions Legend

1 = None

3 = Informal System

5 = More Formal System

N/D = No data available.

3.3 Bottleneck Causes

Interviewed agencies were asked to identify the main causes of bottlenecks in their freeway systems (Table 3.3). The two most frequently reported causes of recurrent freeway bottlenecks by interviewees were capacity restrictions (13 of 14 participants) – a general term that included a range of potential causes such as lane drops, grade increases, narrow lanes, curves, tunnels, bridges, etc. – and weaving sections (13 of 14 participants). Often, interviewees would identify and emphasize specific capacity restrictions that they struggle with in particular. The most frequently mentioned specific capacity restriction (other than weaving sections) was lane drops (3 of 14 participants).

A number of interviewed agency representatives tended to focus more on issues of demand rather than constraints in capacity. Most interviewees acknowledged the importance of demand levels in causing specific bottlenecks in their freeway systems. 10 of 14 participants mentioned that demand surges at on-ramps are a significant cause of bottlenecks. However, three agencies – MTC in the San Francisco Bay Area, the Nevada DOT, and The Netherlands – preferred to focus their attention on the fact that demand exceeds capacity in their entire systems.

Table 3.3 Reported Bottleneck Causes by the Interviewed Agencies

Interviewed Agency	*Demand Surges (On-Ramps)*	*System Demand Exceeds Capacity*	*Lane Drops*	*Grades*	*Narrow Lanes*	*Curves*	*Tunnels*	*Bridges*	*Closely Spaced Interchanges*	*Weaving Sections (Type III)*	*Others*
1) Washington DOT Northwest Region	5	1	3	3	3	3	3	3	5	5	o Double Weaves o Cloverleafs
2) Arizona DOT Valley Transportation Group (Phoenix Metro Area)	5	1	3	3	3	3	3	3	1	5	
3) Caltrans District 4	5	1	3	5	3	3	3	5	1	5	
4) Metropolitan Transportation Commission	1	5	1	1	1	1	1	1	1	1	
5) Nevada DOT	5	5	1	1	1	1	1	1	1	3	
6) North Carolina DOT	5	1	5	5	1	1	1	1	1	3	o Off-ramps that spill back onto freeway.
7) Missouri Department of Transportation	3	1	3	3	3	3	3	3	1	3	o Interchange Design o Demand on cross-freeway facilities.
8) Illinois Tollway Authority	3	1	3	3	3	3	3	3	1	3	o Lack of capacity on cross-freeway facilities.
9) Danish Road Directorate (DRD)	1	1	3	1	1	1	1	1	1	3	o Freeway-to-freeway merges. o Ramp-to-freeway merges.
10) The Netherlands: Ministry of Transport, Public Works and Water Management	5	5	3	3	3	3	3	3	1	5	
11) Wisconsin DOT	1	1	5	1	1	5	1	1	5	5	o Sharp turns/curves. o Left-side entry/exit ramps.
12) Germany: Ministry for Building and Transport, Northrine-Westphalia	3	1	3	3	3	3	3	3	1	3	
13) Pennsylvania Department of Transportation	3	1	3	3	3	3	3	3	1	3	
14) Greece: Attica Tollway Operations & Maintenance Company	1	1	3	3	1	3	3	3	1	3	

Legend
1 = Not a Cause
3 = Sometimes a Cause
5 = Often a Cause
N/A = Not applicable.

Both the Nevada DOT and MTC representatives mentioned that there was far too much traffic on the system overall. The MTC representative said that fully 90 percent of all freeway bottlenecks in the Bay Area are caused by demand exceeding capacity, and therefore, the problem is systemic and cannot be specifically tied to capacity constraints or demand surges at any single location; trying to put the blame on a specific bottleneck location when congestion problems are due to a systemic imbalance of demand and capacity can lead to a misallocation of resources. The representative from The Netherlands gave a historical perspective on how bottlenecks have evolved in their freeway system over time. In that country, the first bottlenecks occurred at locations with identifiable capacity constraints such as bridges and tunnels, but over the years, it was realized that the entire automobile circulation network has become overloaded during the peak periods.

3.4 Performance Measures

Each agency was asked to identify the performance measures they use to analyze freeway bottlenecks (Table 3.4). Eleven of the 14 agencies reported they use *average speed,* the most popular performance measure among the agencies interviewed. This emphasis on speed appears to be widely shared among agencies interviewed in the U.S., but neither The Netherlands nor Germany agency staff reported using this as a performance measure, while the Danish Road Directorate reported they use this measure only "sometimes" when looking at a facility that has multiple bottlenecks. The Nevada DOT is the only US agency interviewed that does not use *average speed* as a performance measure for bottleneck analysis.

Nine of the 14 interviewed agencies reported they use delay (vehicle-hours), eight reported using queue length (miles) and eight reported using extent of congestion (hours). In several cases the agencies interviewed reported the use of unusual performance measure (at least in the sense that the others did not mention using it). MTC staff sometimes use person-hours of delay (as opposed to veh-h of delay) to develop an understanding of how many people (instead of vehicles) are affected by the bottlenecks being studied. However, they also said that this measure was somewhat more time consuming and expensive to obtain since it requires field observations to gather vehicle occupancy data (the number of persons per vehicle). Nevertheless, sending staff into the field to do manual counts was not seen by MTC (or by Caltrans District 4) staff simply as an added burden. Both agencies' interviewees emphasized that there is great value in getting analysts away from their offices and out into the field to observe the operation of the freeway system first-hand. These outings provide analysts with a level of understanding of local conditions and how bottlenecks function in "real-time" that remote/numerical analysis cannot.

Of the 14 participants, two agencies – Pennsylvania DOT and Wisconsin DOT – reported they are currently or will soon be using safety as a performance measure. Their inclusion of a non-mobility measure within their performance analysis toolkits suggests there may be a shift underway in thinking about freeway performance measures and the analysis of bottlenecks in particular. Interview participants with San Francisco Bay Area agencies (i.e., MTC and Caltrans District 4) both mentioned how lane restriping used to be a favorite low-cost bottleneck improvement that has recently seen a "backlash" from within Caltrans due to concerns that they have sacrificed safety in favor of improvements in mobility. By including safety as a performance measure for evaluating bottlenecks and their associated improvements, Pennsylvania and Wisconsin DOTs may signal a change in approach to analyzing and improving freeway bottlenecks.

Table 3.4 Performance Measures Used by the In*terviewed Agencies

	Interviewed Agency	*Average Speed*	*Throughput (Discharge Vol.)*	*Queue Length*	*Delay (veh-hrs)*	*Extent of Congestion (hrs)*	*Others*
1)	Washington DOT Northwest Region	5	5	1	1	5	Travel Times
2)	Arizona DOT Valley Transportation Group (Phoenix Metro Area)	5	1	5	5	5	LOS (HCM)
3)	Caltrans District 4	5	5	5	5	1	# of Bottlenecks
4)	Metropolitan Transportation Commission	5	1	1	5	1	Person-Hrs. Delay
5)	Nevada DOT	1	1	1	5	1	LOS
6)	North Carolina DOT	5	1	5	5	5	Density
7)	Missouri Department of Transportation	5	5	5	5	5	
8)	Illinois Tollway Authority	5	5	5	5	5	LOS
9)	Danish Road Directorate (DRD)	3	3	3	1	1	Demand/Cap.
10)	The Netherlands: Ministry of Transport, Public Works and Water Management	1	1	1	1	1	Queue-Weight
11)	Wisconsin DOT	5	5	5	5	3	Safety
12)	Germany: Ministry for Building and Transport, Northrine-Westphalia	1	1	1	1	5	
13)	Pennsylvania Department of Transportation	5	5	5	5	5	Safety
14)	Greece: Attica Tollway Operations & Maintenance Company	5	5	5	1	5	

Legend
1 = Not Used
3 = Used Sometimes
5 = Often Used

3.5 Data Sources

A follow-up question asked what sources of data they use for developing these performance measures. Responses to this question are summarized in Table 3.5. Most of the agencies (12 out of the 14 participants) reported they use loop detector data and five reported using either (or both) probe vehicles.

Nine out of 14 agencies reported they use manual counting methods though more than half (5) said they use them infrequently. Most of these agencies said they use manual counts either as a quality check on detector data, in situations where they do not have operational detectors, as a means to do vehicle occupancy or classification counts, or simply as a way to get analysts out into the field and develop first-hand knowledge and understanding of traffic conditions in the study area.

Eight of the 14 survey participants said they use cameras as a bottleneck analysis data source, although several mentioned that they tend to use cameras to informally identify bottleneck locations and not as a primary data source for quantitative analysis. Three agencies also indicated that the camera coverage of their freeway networks tends to be incomplete or geographically focused (e.g.; only covering metropolitan area freeways), further limiting their potential usefulness.

Table 3.5 Data Sources Used by the Interviewed Agencies

	Agency	*Loops*	*RADAR*	*Cameras*	*Probes*	*Floating Cars*	*Manual Counts*	*Others*
1)	Washington DOT Northwest Region	5	5	1	5	5	1	
2)	Arizona DOT Valley Transportation Group (Phoenix Metro Area)	5	1	5	5	5	3	Acoustic (PADs)
3)	Caltrans District 4	5	1	1	1	5	3	Tubes
4)	Metropolitan Transportation Commission	5	1	1	1	5	3	Tubes
5)	Nevada DOT	5	1	3	1	1	5	Weigh-In-Motion
6)	North Carolina DOT	3	3	3	1	1	5	
7)	Missouri Department of Transportation	1	5	5	5	3	1	
8)	Illinois Tollway Authority	1	1	5	1	1	5	
9)	Danish Road Directorate (DRD)	5	3	1	1	1	1	
10)	The Netherlands: Ministry of Transport, Public Works and Water Management	5	1	1	3	1	1	
11)	Wisconsin DOT	5	1	3	1	1	1	
12)	Germany: Ministry for Building and Transport, Northrine-Westphalia	5	1	1	1	1	3	
13)	Pennsylvania Department of Transportation	5	1	5	1	1	5	Traffic.com
14)	Greece: Attica Tollway Operations & Maintenance Company	5	1	5	1	1	3	

Definitions Legend

1 = None

3 = Informal System

5 = More Formal System

3.6 Use of Analysis Techniques

Agency representatives were asked to identify which analytic techniques/methods they use to analyze freeway bottlenecks. Table 3.6 summarizes their responses.

Thirteen out of the 14 respondents said they use the HCM methods, making it the most widely used analytic tool for bottleneck analysis. Two of the three Caltrans District 4 interviewees indicated that they do not generally like to use HCM methods because Bay Area drivers are different from the rest of the country as represented in the HCM methods.

Sketch planning methods and simple analytical techniques (e.g., queuing diagram) were found to be used least often of the three technique categories (Five out of 14 responding agencies). The Danish Road Directorate representative reported the use of arrival/departure sketch calculations for road construction project site analysis, while the MTC representative reported that their staff does not employ these methods but that they are used by their colleagues at Caltrans District 4. MTC's representative also mentioned that while sketch planning tools are inexpensive and relatively quick to implement, they lack sufficient details for use in environmental documents.

Eleven out of 14 agencies reported using simulation modeling techniques. Of those that did not use them or of those who did but used them for limited, project-level applications, they found simulation models to be expensive, labor-intensive and difficult to calibrate. The interviewed representative of the Washington DOT Northwest Region specifically mentioned that they do not generally use simulation models because the weather conditions and driving behaviors of Seattle area residents are substantially different from those around the rest of the country, making them difficult to calibrate. In addition to the high costs of simulation models, the Wisconsin DOT representative also mentioned that they are generally not sensitive to minor geometric improvements. This can be an impediment to analyzing viable low-cost bottleneck improvements. Caltrans District 4 interviewees also mentioned the difficulties and expense of using simulation models, but they have found ways to overcome these shortcomings by using FREQ, which has several distinct advantages. First, it is a simulation model that was developed at the nearby University of California, Berkeley campus, allowing for a close working relationship between the software developers and Caltrans staff. FREQ is also less expensive than other simulation models, due in part to its lack of complex graphical display capabilities that drive up the costs of development for other software packages. Its relative simplicity is also an advantage in terms of the costs of using and implementing the model, which are low compared to other packages. However, on the downside, its lack of graphical display capabilities makes it less useful than other packages for use in public presentations.

Table 3.6 Modeling Tools Used by the Interviewed Agencies

	Interviewed Agency	*Sketch Planning*	*HCM*	*Simulation*
1)	Washington DOT Northwest Region	1	5	1
2)	Arizona DOT Valley Transportation Group (Phoenix Metro Area)	5	5	3
3)	Caltrans District 4	5	3	5
4)	Metropolitan Transportation Commission	3	3	5
5)	Nevada DOT	1	3	1
6)	North Carolina DOT	1	5	5
7)	Missouri Department of Transportation	1	5	5
8)	Illinois Tollway Authority	1	5	5
9)	Danish Road Directorate (DRD)	3	5	1
10)	The Netherlands: Ministry of Transport, Public Works and Water Management	1	1	5
11)	Wisconsin DOT	1	5	5
12)	Germany: Ministry for Building and Transport, Northrine-Westphalia	1	5	3
13)	Pennsylvania Department of Transportation	1	5	5

Legend
1 = Not Used
3 = Used Sometimes
5 = Often Used
N/A = Not applicable.
N/D = No data available.

The MTC representative agreed that the costs of using simulation models in terms of time and resources are high – not only in terms of the time and money spent on model coding and analysis, but also in terms of the opportunity costs for analyst staff time. In general, the MTC interviewee feels that in the traffic engineering community in general, analysts tend to spend too much time in the office and working on computers and not enough doing field observations of traffic conditions. More data/time-intensive methods (like simulation models) tend to exacerbate this problem.

The Nevada DOT representative echoed the importance of doing field observations as well as informal, sketch planning analysis. In particular, the geographic scale of analysis is a potential barrier to identifying low-cost bottleneck solutions. Most of their congestion analysis is currently done at a broad scale which tends to miss identifying individual bottleneck locations, their causes, and opportunities for low-cost bottleneck solutions. To make up for this shortcoming, Nevada DOT analysts engage in field observations, sketch planning, and other informal analysis techniques that can capture these small-scale, site-specific details at individual bottleneck locations.

3.7 Use of Low-Cost Bottleneck Improvements

Interviewed representatives were also asked to name the low-cost improvements that their agencies have used at bottleneck locations in their jurisdictions (Table 3.7). The most frequently mentioned low-cost bottleneck improvements either analyzed or implemented by the interviewed agencies were: ramp metering (7), auxiliary lanes (6), and HOV lanes (4). While lane width reductions/restriping was mentioned by three respondents, there were comments from the San Francisco Bay Area agencies (Caltrans and MTC) that many of these opportunity locations have already been converted, and there is now a hesitancy to use in additional locations since many within Caltrans believe that safety has suffered for the sake of capacity enhancement at sites where restriping has already been done.

In general, the interview responses to this question suggest there is a trend towards favoring the implementation of ramp metering as a low cost bottleneck improvement. Intelligent Transportation System (ITS) applications have been growing in popularity for more than a decade, but ramp metering systems are particularly attractive since they allow traffic managers to directly control the freeway traffic demand. This unique capability provides a valuable tool for managing freeway bottlenecks that does not involve large and expensive capacity expansions. One of the Caltrans District 4 interviewees mentioned that the two most frequently implemented low-cost improvements are ramp metering and "taking" shoulders in the San Francisco Bay Area.

Overall, auxiliary lanes were the second most popular reported improvement, and from the pattern of responses to our interview questions, it appears that they are more popular in the United States than in Europe. The only European interview subject to mention using auxiliary lanes as a tool to address freeway bottlenecks was the Danish Road Directorate where they had performed a test implementation using auxiliary lanes. However, this experience appears to have had limited success and additional applications of this method were not pursued. In The Netherlands where legislative changes and environmental issues have discouraged the use of infrastructure changes to address freeway bottlenecks, the Ministry of Transport, Public Works and Water Management has mostly pursued ITS-based improvements such as speed smoothing, dynamic lanes, dynamic road information panels (DRIPs), and ramp metering.

The Missouri DOT representative reported that auxiliary lanes are not a "sure fire" solution to bottleneck congestion problems. When the driving public is not familiar with them, auxiliary lanes can increase the amount of lane-changing actions on a freeway segment, reducing the beneficial effects of these improvements. The Missouri interviewee suggested that in order to reap the full benefits of the auxiliary lane investments, implementing agencies may need to put efforts into educating the driving public on their use.

HOV lanes, the third most popular improvement based on the interview responses, appear most popular with faster growing western and southern U.S. states – states such as California, Washington, Arizona and North Carolina. Based on these interviews, it appears that HOV lanes are popular with fast-growing areas because they attack the problems of congestion at several levels. First, assuming they are implemented as part of a freeway widening project (i.e., they do not take away existing lanes of traffic), they add capacity, and in doing so, can address congestion problems at multiple individual bottleneck locations as well as the corridor level. Second, HOV lanes can also affect traffic demand by encouraging carpooling and transit ridership. The ability to affect both the supply and demand sides of the congestion equation makes this improvement particularly attractive to communities that are may be struggling to accommodate rapid growth, while the high costs of HOV lane construction make it less attractive to areas that do not have the economic growth needed to fund them.

In the San Francisco Bay Area, the Caltrans District 4 representative reported that there is currently a "big push" underway in the Bay Area for HOV lane implementation as a low-cost freeway bottleneck improvement. In previous years, there was a great deal of controversy and questioning from the public as to the efficacy of HOV lanes. Caltrans was frequently on the defensive and they routinely performed "before and after" studies of HOV implementations to help justify their use as effective measures for congestion relief. Recently, the controversies over HOV lanes have subsided, and Caltrans has stopped routinely performing these studies.

Analysis of the interviews suggests there are differences in approach to low-cost bottleneck improvements between the U.S. and European agencies. While there are exceptions, the European agencies appear to favor "dynamic" bottleneck improvements – which tend to use ITS applications to re-route traffic using traveler information, or engage dynamic lanes – while agencies in the U.S. tend to use more "static" improvements, such as the construction of auxiliary or HOV lanes. Ramp metering in the main exception which seems to be popular with both the U.S. and European interviewed agencies.

Agency	Auxiliary Lanes	Collector- Distributor Rd.	Paved Right Shoulder	Paved Left Shoulder	Shoulder / Plus Lane	Re-Stripping to add more, narrower lanes	All-Purpose Lane (concurrent or reversible)	HOV Lanes, (Concurrent or Reversible)	Truck Restrictions	Ramp Metering	Temporary Ramp Closures	Traveler Info. / Traffic Diversion Info.	Ramp Widening / Improvements	Freeway-to-Freeway HOV Ramps	Taking Shoulders for Lanes of Travel	Early Double-Striping for Major Diverges	Others
1) Washington DOT Northwest Region	1	1	1	1	3	1	5	5	1	5	1	5	1	1	1	1	
2) Arizona DOT Valley Transportation Group (Phoenix Metro Area)	5	1	1	1	5	5	1	5	1	5	1	1	1	1	5	1	Add lane by restriping and removing HOV buffer.
3) Caltrans District 4	5	1	1	1	1	5	1	5	1	5	1	1	5	5	5	1	
4) Metropolitan Transportation Commission	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	
5) Nevada DOT	1	1	1	1	1	1	1	1	1	3	1	1	3	1	1	1	
6) North Carolina DOT	5	1	1	1	1	1	1	5	1	1	1	1	1	1	1	1	
7) Missouri Department of Transportation	5	1	1	1	1	1	5	1	1	1	1	5	3	1	3	5	Early Double-Striping for Major Diverges
8) Illinois Tollway Authority	5	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	Converting weaving operations to Type B.
9) Danish Road Directorate (DRD)	3	1	1	1	1	1	1	1	1	3	1	1	1	1	1	1	
10) The Netherlands: Ministry of Transport, Public Works and Water Management	1	1	1	1	1	1	1	1	1	5	1	5	1	1	1	1	o Dynamic Lanes o Speed Smoothing
11) Wisconsin DOT	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	
12) Germany: Ministry for Building and Transport, Northrine-Westphalia	1	1	5	1	1	1	1	1	1	5	1	1	1	1	1	1	Interchange Modifications
13) Pennsylvania Department of Transportation	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	
14) Greece: Attica Tollway Operations & Maintenance Company	1	1	1	1	1	1	6	1	1	1	1	1	1	1	1	1	Re-alignment

Legend
1 = Not Used
3 = Used Sometimes
5 = Often Used
N/A = Not applicable. MTC is a transportation planning and financing agency, so it does not directly implement bottleneck improvements. For Bay Area improvements, see Caltrans District 4 responses above.
N/D = No data available.

Table 3.7 Bottleneck Improvements Reported by the Interviewed Agencies

3.8 Benefits and Costs of Bottleneck Improvements

Understanding the benefits and costs of a low-cost freeway bottleneck improvement requires post-construction analysis and evaluation. However, based on the interview responses for this project, only five of the agencies interviewed indicated they have undertaken post-construction evaluations of freeway bottleneck improvements. Three of these were specifically mentioned as being ramp metering effectiveness evaluations, which have been needed to maintain or improve political and public support for this sometimes controversial method. Of the 14 interviewed agencies, only two said they routinely perform post-construction evaluations.

Due in part to the paucity of post-construction evaluations, there was very little data on the actual costs and benefits of low-cost bottleneck improvements gathered through the interviews. Interviewed agencies reported that the low-cost bottleneck improvement projects undertaken generally fall in the range of costing between a few thousand dollars (for restriping projects) to around $2.5 million (for adding auxiliary lanes). Ramp metering is considered very inexpensive if the equipment is already installed and the intervention involves the retiming of signals or the active monitoring and adjustment of signals by transportation managers. Ramp metering installation project costs are generally in the range of $100,000 to $250,000 per entrance ramp.

There was even less information available on the benefits of these improvements. Many interviewees responded to this question qualitatively by stating they considered their benefits to be “congestion” or “bottleneck relief” (3) or with “improved traffic flow” (2). Caltrans District 4 and MTC conducted a “before” and “after” study of ramp metering implementation on I-580 through Pleasanton and Livermore in San Francisco Bay Area. While the benefits and costs were not monetized, the implementation of ramp metering was found to increase traffic volumes and average speeds in the area where the metering system was installed, but it was also measured that the next downstream bottleneck (approaching the Altamont Pass area) was made worse due to the increased upstream flows.

Wisconsin DOT has performed an evaluation of a ramp metering system implementation project on a bottleneck on US45 in Milwaukee County. This evaluation found that while ramp metering increased speeds on the study freeway segments ranging from six to 13 percent in areas where the bottleneck usually occurred, and for the entire freeway study segment (including areas where the bottleneck did not occur and free flow conditions were the norm), speeds increased an average of four percent. While ramp metering increased speeds and decreased total vehicle-hours of travel on the freeway mainline by roughly five percent, the added delay on the ramp metered on-ramps resulted in a net delay reduction of only two percent. Overall, the VMT in the study corridor increased by two percent following the ramp metering implementation.

3.9 Funding and Programming of Bottleneck Initiatives: Follow-Up Interviews

Following the fourteen interviews discussed above, four additional interviews were performed with operational and financing agencies (Puget Sound Regional Council, Caltrans, Florida DOT, and the Maryland State Highway Administration) to identify the approaches and methods used to fund low-cost bottleneck initiatives. Of these agencies, the most active and vigorous at programming and funding low-cost bottleneck improvement projects are also those that have developed and engaged in partnerships with transportation stakeholders. Inter-agency partnerships seem to be the “zeitgeist” in the transportation planning and policy arenas – everybody seems to be involved in them and everyone talks about how important they are. But in the case of programming and funding freeway bottleneck projects, it is clear that partnerships serve a valuable purpose. Low-cost bottleneck projects are attractive because they have the potential for big payoffs from small investments. However, big investments also have big political profiles while small investments can pass-by largely unnoticed, no matter how effective they are. As a result, low-cost bottleneck improvements often have trouble competing against capital-intensive, large ones. The bottom line is politicians like to attend ribbon-cutting ceremonies for big projects, which makes them more likely to receive funding. The interviews conducted here suggest that there are three (not mutually exclusive) ways to garner funding for these underappreciated yet effective low-cost bottleneck projects.

First, as suggested, partnerships between local governments, state DOTs, MPOs, and other interested stakeholders can create a political groundswell that bring the attention needed to low-cost bottleneck improvements. With attention, funding can follow. A second approach calls for creating a consistent, performance measure-based planning and evaluation system to identify bottlenecks and analyze the best alternative interventions. In doing this, a more “level playing field” is created that can bring the underappreciated qualities of low-cost bottleneck improvements to the attention of decision-makers in charge of funding projects. The third approach involves creating a stand-alone low-cost bottleneck funding program that will ensure the viability of low-cost bottleneck projects.

Puget Sound Regional Council

The Puget Sound Regional Council (PSRC) provides an example of how to combine the above described approaches. PSRC has undertaken a planning partnership with the local governments, Washington DOT (WSDOT), local transit agencies, and other transportation system stakeholders to develop a Congestion Management Program (CMP), which emphasizes inter-agency coordination on bottleneck identification, analysis, improvements selection and funding. Through partnership meetings and planning sessions, the new CMP process identifies a unified framework for identifying and analyzing bottlenecks. Previously, individual corridor and bottleneck studies were done independently either by local governments, WSDOT, or PSRC. The new CMP process unifies these efforts, providing a common framework that can be applied to understand where the bottlenecks are and how they can be addressed. It will also allow bottlenecks and their potential improvement projects to be compared and valued using a common analytic, performance measure-based system. This will make prioritization, programming and funding efforts more straight-forward, even-handed and cost-effective while the partnerships serve to create a constituency of support for these projects.

However, PSRC realizes that despite the benefits of partnerships and a coordinated system for identifying and evaluating bottlenecks, low-cost bottleneck solutions may still suffer when compared to more high-profile projects. While there is currently no funding category within Washington State solely dedicated to financing low-cost bottleneck solutions, PSRC and its partners are considering this approach as a way to ensure the viability of low-cost improvements within their CMP process.

Caltrans

Despite its large size and budgetary difficulties in recent years, the State of California’s Department of Transportation (Caltrans) has created a comprehensive and cooperative framework similar to PSRC’s. Caltrans’ operational planning is guided by the Transportation Management System Master Plan (TSMP) which provides guidelines for the types of strategies that should be pursued to improve congestion. The plan provides direction to the Caltrans local districts (which are semi-independent operations) while offering them enough flexibility in its execution to innovate and for working partnerships to evolve. Similar to PSRC’s approach, Caltrans’ first priority rests upon comprehensive, coordinated, and consistent system monitoring and evaluation. By using these data to analyze the transportation system and identify where the bottlenecks occur, they can then identify and prioritize intervention strategies on higher levels of the pyramid such as system maintenance, smart growth, ITS solutions, operational improvements, and finally system expansions to fulfill critical needs.

Also similar to PSRC’s approach, the Caltrans model can be molded to incorporate the concerns and priorities of partner agencies and stakeholder groups. It does this by incorporating other planning efforts into the statewide plan's framework. For example, to operationalize the statewide plan, California has initiated Corridor System Management Plans (CSMPs) for major state corridors. The plans address all modes, the available capacity of each, and spell-out how to manage and maximize the available capacity. These plans are developed in partnership with local partners and are made consistent with these agencies' Congestion Management Plans, Regional Transportation Plans and Long Range Transit Plans (LRTP). By coordinating these locally-produced plans with the TSMP, Caltrans is able to identify a set of bottleneck projects that will have reinforcing support for funding from the local agencies as well.

Finally, to ensure these plans (with their bottleneck improvement projects) come to reality, Caltrans has developed Corridor Mobility Improvement Account (CMIA) which funds (among other projects) bottleneck improvements. Caltrans District 7 provides an example of how this interlocking system of general policy guidance (in the form of the Transportation Management System Master Plan) provided by the upper levels of Caltrans can provide a framework upon which local partnerships can flourish and be innovative. This district is responsible for the state highway system in Los Angeles and Ventura counties. Due in part to the near-ubiquitous levels of congestion in the LA basin and the lack of affordable real estate with which to build new facilities, District 7 has been aggressive in identifying strategies to manage freeway congestion by controlling access to the system. This has allowed operations efforts to be concentrated along access and interchange points and to build a strong foundation of monitoring and control infrastructure (i.e., they have a strong a legacy of roadside instrumentation and software development). This strong foundation of system monitoring and evaluation enables District 7 to implement a cost-effective and comprehensive set of ITS bottleneck improvements – a bottleneck improvement strategy they have more-or-less defined and implemented for themselves in cooperation with local governments and the MPO.

Caltrans Headquarters further encourages cooperation and partnerships between its districts and partners by structuring their funding and project programming processes to encourage these activities. While there is no direct funding category for bottlenecks, bottleneck projects are routinely programmed, approved through the normal state budgetary processes, and funded by the legislature. Therefore, the Transportation Management System Master Plan effectively sets the guidelines by which the state tells the districts and their local partners what plans and strategies will be likely to receive funding support from the state, and as such represents a kind of funding commitment from the state for projects that meet the goals of the plan.

California's governor and Caltrans have also developed the Go California program – a $1.3 billion statewide program intended to rapidly deploy transportation improvement measures based on public-private partnerships and design build within an 18 month time frame. While this program is a one-time measure intended to fund the rapid deployment of transportation projects, its project selection and funding processes have a similar emphasis to those governing the Transportation Management System Master Plan. Projects are selected by the local MPOs and with the only requirement that they need to be able to complete them within an 18 month timeframe and the requested budget. District 7 has used this program to fund auxiliary lanes, message sings, and timing improvements to address bottlenecks.

The flexibility and sheer variety of funding options available to Caltrans' districts provides fertile ground for planning and technical innovations. The Corridor System Management Planning (CCSMP) program provides the programming justification for funding the project from the Caltrans Operations and Maintenance Special Programs budget. In this way, locally initiated and selected bottleneck improvement projects are encouraged by the state, while these projects are also encouraged to be tuned and refined to fit the goals and requirements of Caltrans Headquarters and the politicians in Sacramento. Of course, local initiatives are more likely to succeed when local funding sources are available. In the case of District 7, the sources of funding for all transportation projects in the Los Angeles region are atypical compared to other areas: local funding dominates (Figure 3.1). So while Caltrans does not have a dedicated source of funds for low-cost bottleneck projects, it has been able to use its local funding sources to leverage state and federal funds, increasing the competitiveness of these projects in the funding process.

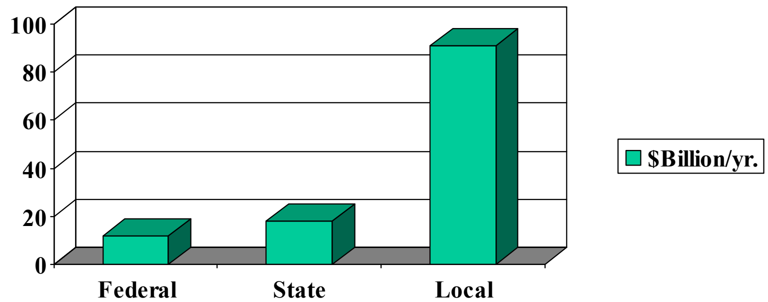


Figure 3.1 Los Angeles Region - Transportation Projects by Source (2002-2030)

Florida Department of Transportation

Florida DOT provides a typical example of how bottleneck improvement projects are programmed and funded by state-level agencies. Like most large DOTs, FDOT has experienced delays in project implementation due to the long lead-times required for project identification, planning, design, funding, and construction. In FDOT's experience, once a project is identified it may be five years before it can get funded since district funds are already fully programmed far into the future. One way to short-circuit this process is to identify a dedicated funding source for quick-delivery projects. Like California, there is no direct funding category for bottlenecks in Florida. However, similar to the Go California funding program, FDOT and the state legislature have developed a series of one-time funding programs designed to speed up project delivery. FDOT had a category of state funds called "Operational Quick-Fixes", which funded activities such as restriping and adding dual turn lanes to interchanges. While this funding program is technically still open, it was not funded in 2006. More recently, FDOT has funded bottleneck-related projects under the Strategic Intermodal System (SIS) Connector program. $100 million were allocated to roughly 50 projects focused on sea- and air-ports access. FDOT is trying to "stay ahead" of major distribution centers, which are being quickly developed across the State. These generate significant truck traffic that may result in a need for bottleneck relief improvements. FDOT is trying to identify improvements prior to construction, rather than after the fact.

Florida DOT's District 7 has been able to find local sources of funding for bottleneck improvements by using Developments of Regional Impact (DRI) fees. Often these funds are pooled so that larger projects can be implemented than would be possible using fees from individual developments. FDOT has found that low-cost bottleneck projects are well-suited for DRI funding. At the FDOT district-level, sub-DRI funds are increasingly being used for low-cost congestion projects. Sub-DRIs are below the threshold for a full DRI but are expected to generate impacts. By State Statute, a sub-DRI must pay a proportionate share to their level of expected impact, including traffic impacts. FDOT districts partner with local governments to pool sub-DRI funds to address traffic problems.

Maryland State Highway Administration

Interview participants at the Maryland State Highway Administration (SHA) emphasized the need for flexibility in funding programs. While new sources funding dedicated to low-cost bottleneck projects is always helpful, too many restrictions on use of the money can be a hindrance to meeting the needs of a bottleneck improvements program. However, SHA has increasingly become aware of the fact that low-cost bottleneck projects have trouble competing against more high-profile projects since they "do not lend themselves to ribbon cutting." To compensate, SHA often looks for opportunities where these projects can serve multiple purposes and attract funding from other sources. For example, locations with congestion problems often pose safety problems as well. Hazard Elimination (HES) Program funds are frequently used to address these problems.

SHA interviewees also emphasized the importance of publicizing congestion relief projects as a way to increase political support and funding opportunities. SHA is currently considering a program with its partners to develop a set of comprehensive and consistent performance measures to help raise support for bottleneck projects. Publishing and promoting "state of the system" reports that highlight bottleneck locations is one approach SHA and the regional agencies have been working on. The Baltimore Metropolitan Council has developed congestion reports based on aerial (Skycomp) data and speed/delay runs and have found this to be a useful communications tool. SHA's partners have also been encouraging the use of low-cost approaches to bottleneck problems. FHWA has been encouraging SHA engineers to look at low-cost improvements for its state highway system bottlenecks.

Maryland has also been using developer impact fees to fund bottleneck improvements, similar to the approach used in Florida. The State's requirement that there be "adequate strength of new facilities" requires traffic studies for developments of 750 or more dwelling units and thresholds of commercial development that vary with the type of facility and location. These funds help stretch public dollars and leverage funding from other sources. Some counties, including Frederick and Howard, have impact fee programs that enable them to pool impact fee money from multiple developments and fund larger, corridor-oriented projects. Often, the approach to funding a low-cost bottleneck project will be different for different areas – the availability of local, state, and federal funds varies depending on the facility, its problems and its location. Determining the best approach for each project requires active state, regional, and local partnerships that can effectively coordinate the evaluation, planning and budgeting of bottleneck solutions.

3.10 Summary and Conclusions

In the analysis of the two interview survey efforts conducted – the interviews with operating agencies and the follow-up interviews of funding and programming activities – the following findings are worthy of note:

- Speed was the most frequently reported basis for bottleneck definitions and accordingly, the most popular performance measure used was *average speed*. Typically, those agencies using speed measures also have more formalized definitions for identifying bottlenecks.
- This emphasis on speed appears to be widely shared among agencies interviewed in the U.S., but was not shared by the three European agencies interviewed.
- The two most frequently reported causes of recurrent freeway bottlenecks by interviewees were capacity restrictions and weaving sections. While most interviewees also mentioned that demand surges at on-ramps are a significant cause of bottlenecks, three agencies preferred to focus their attention on the fact that demand exceeds capacity in their entire systems.
- Most of the agencies reported using loop detector data but several agencies mentioned the value of manual counting methods and site surveys to ensure their engineers are familiar with the study sites and are not becoming over-reliant on computer analysis techniques.
- Questions related to analysis techniques used to evaluate bottlenecks yielded the following insights:
    - HCM methods were the most widely used analytic tool for bottleneck analysis,

- Simulation modeling techniques are being widely used as well but for more specific, project-level applications since they tend to be expensive, labor-intensive and difficult to calibrate, and
- Sketch planning methods and simple analytical techniques (e.g., queuing diagrams) were used least often due in part to the fact that they do not provide sufficient details for use in environmental documents.

- The most frequently mentioned low-cost bottleneck improvements were: ramp metering (7), auxiliary lanes (6), and HOV lanes (4). While lane width reductions/restriping were mentioned by three respondents, two agencies mentioned that many of these opportunity locations have already been converted, and there is now a hesitancy to reduce lane widths due to safety concerns.

- There appears to be a trend towards favoring ramp metering as a low cost bottleneck improvement, perhaps in part due to the fact that they allow direct control freeway demand levels.

- Interview results suggest there are differences in approach to low-cost bottleneck improvements between the U.S. and European agencies. European agencies appear to favor "dynamic" bottleneck improvements – which tend to use ITS applications to re-route traffic using traveler information, or engage dynamic lanes – while agencies in the U.S. tend to use more "static" improvements, such as the construction of auxiliary or HOV lanes. Ramp metering is an exception which seems to be popular both in the U.S. and Europe.

- Only five of the agencies interviewed indicated they have undertaken post-construction evaluations of freeway bottleneck improvements. Three of these were ramp metering effectiveness evaluations which have been needed to maintain or improve political and public support for this sometimes controversial method. Of the 14 interviewed agencies, only two said they routinely perform post-construction evaluations.

- Post-project evaluation studies in the San Francisco Bay Area and Milwaukee County, Wisconsin both found that while improvements successfully reduced congestion at the project bottleneck sites, congestion at downstream bottlenecks and off-freeway ramps and surface streets tended to reduce the delay and speed benefits overall.

- The interviews suggest there are three (not mutually exclusive) ways to garner funding for low-cost bottleneck projects:

  - Partnerships between local governments, state DOTs, MPOs, and other stakeholders can create a political groundswell that brings attention to low-cost bottleneck improvements,
  - Creating consistent, performance measure-based planning and evaluation systems to identify bottlenecks and analyze the best interventions, and
  - Creating a stand-alone low-cost bottleneck funding program.

- A number of the funding interviewees mentioned the importance of making sure bottleneck improvement projects can compete against higher profile construction projects:

  - The Puget Sound Regional Council is considering a dedicated funding category within Washington State for financing low-cost bottleneck solutions,
  - Caltrans has developed Corridor Mobility Improvement Account (CMIA) which funds (among other projects) bottleneck improvements,
  - Florida DOT's District 7 has been able to find local sources of funding for bottleneck improvements by using Developments of Regional Impact (DRI) fees, and

- The Maryland State Highway Administration looks for opportunities where bottleneck projects can serve multiple purposes and attract funding from other sources. For example, locations with congestion problems often pose safety problems as well. Hazard Elimination (HES) Program funds are frequently used to address these problems.

CHAPTER 4

FRAMEWORK FOR ANALYSIS OF FREEWAY BOTTLENECKS

This Chapter presents a working definition of recurring freeway bottlenecks for existing and projected conditions, and a matrix of bottleneck causes and associated low-cost improvements based on the findings from the review of literature and the interviews with operating agencies. Next, a framework for the analysis of freeway bottlenecks is presented. The use of real-time data and modeling tools in bottleneck analysis are described and an on-line algorithm for automatic bottleneck identification is presented.

4.1 Definition of Freeway Bottlenecks

There are different definitions depending on whether the analysis is concerned with existing or future (*projected)* freeway bottlenecks. An *existing* recurring bottleneck is defined based on field measurements according to the following criteria:

- Speeds upstream of the bottleneck are less than 30 mph. Speeds at the bottleneck location range between 40 to 60 mph depending of the measurement location (vehicles accelerate as they travel through the bottleneck). Traffic is free-flowing downstream with speeds at or near free-flow speeds (typically above 60 mph). Detector occupancy values are generally above 30 percent upstream, and less than 10 percent downstream of the bottleneck location.
- Activation times and locations are reproducible over typical weekdays. The start and length of the activation period (duration of congestion) may vary over days because of the variability in traffic demands. Past studies and extensive analyses of detector data show a minimum activation time of continuous 30 minutes. In our bottleneck identification methodology [20] we used the criterion of bottleneck activation for 90 percent of the days analyzed (minimum of three months of data).

A projected bottleneck can be defined as a freeway segment that has a projected demand/capacity (d/c) ratio is greater than 1 for the selected time interval of analysis (typically 15 minutes). In this case, the volume (hourly flow) through the bottleneck will be equal to the capacity and the excess demand (d-c) will be stored upstream of the bottleneck section (in the form of a queue). There are several parameters that can contribute to d/c > 1.0 including:

- Increase in traffic demand over normal capacity (e.g. at on–ramps)
- Increased heavy vehicle demand, particularly on long, steep upgrades. The HCM procedures increase the total traffic demand by using the heavy vehicle adjustment factor f_{HV}
- All geometric elements that reduce the free-flow speed (FFS), because the capacity is a function of FFS according to HCM: narrow lanes, tunnels, horizontal curves, lateral obstructions, etc.
- Capacity of weaving sections, which is dependent not only on the section design (weaving section configuration) but also on the intensity of lane-changing maneuvers (ratio of weaving to non weaving traffic)

Note that the definition and classification of projected bottlenecks requires the use of modeling tools to determine the capacity of the existing section and the projected traffic demands.

4.2 Bottleneck Classification

We classify recurrent freeway bottlenecks into three types by considering the demand and capacity characteristics of the facility in question:

Type I bottleneck: demand surge bottleneck, no capacity reduction
Type II bottleneck: capacity reduction bottleneck, no demand surge
Type III bottleneck: combined demand surge and capacity reduction

Type I bottlenecks typically occur at a freeway on-ramp merge locations. Since local demand conditions at these locations cause the bottlenecks, the most effective solutions – both in terms of cost and bottleneck relief – are those that directly affect and moderate demand surges. Capacity increases in the bottleneck section may simply move the demand surge downstream to the next section. The findings from the literature review and the interviews with operating agencies suggest that there are two approaches to addressing Type I bottlenecks: local facility scale demand management techniques (ramp metering being the best example) and global strategies to address system-wide problems of demand exceeding capacity. Three of the surveyed agencies said that one of the most important reasons for recurrent bottlenecks in their systems was that the total demand exceeds the total capacity/supply for their freeway network (MTC, Nevada DOT, and The Netherlands), whereas virtually all the respondent agencies – with the exception of MTC, Wisconsin DOT, the Attica Tollway Company (Greece) and the Danish Road Directorate – reported that more localized demand surges at on-ramps were a primary cause of their recurrent bottlenecks.

Type II bottlenecks occur where there is a change in the freeway geometry (lane drop, upgrade, horizontal curve, etc.) Other sections of the freeway upstream and downstream have higher capacity than the specific bottleneck section. Our survey findings suggest that while demand metering is generally not cost-effective for Type II bottlenecks (unless there is a nearby on-ramp upstream that can be metered), limited capacity improvements through the bottleneck section however can be quite effective. Agency representatives who tended to mention capacity restrictions as important causes for their freeway bottlenecks also tended to report favoring adding auxiliary lanes, use of shoulders as travel lanes, and restriping to add narrow lane(s), as improvements to address these problems. These improvements share a common scale, in that they are all geographically limited and generally, low-cost capacity improvements.

Type III bottlenecks – which occur mostly in weaving sections – are the most difficult to solve because they often combine a demand surge with a capacity reduction associated with weaving. This intertwined relationship of causality implies that solutions need to be similarly multifaceted. Our survey work found that agencies that face Type III bottlenecks in their freeway systems often combine demand metering and capacity enhancements to address these problem locations. All respondent agency representatives that listed weaving sections as an important cause of recurrent bottlenecks also reported using ramp metering as a frequently used improvement measure (Washington DOT, Arizona DOT, Caltrans District 4, and The Netherlands). Similarly, those agencies that reported weaving sections as an important cause of recurrent bottlenecks in their jurisdictions, also reported favoring local improvements – as seen for Type II bottleneck types – e.g., auxiliary lanes, use of shoulder (plus lane), and re-stripping to add new lanes.

Diverge bottlenecks, when queues on freeway off-ramps spillback onto the freeway mainline, is another example of Type III bottlenecks, that may be caused by heavy off-ramp traffic and/or insufficient capacity at the downstream end of the off-ramp. Ramp metering in this case may be of little benefit because it may increase the rate of exiting vehicles causing additional spillback on the freeway [60]. Potential solutions involve localized freeway capacity enhancements such as adding auxiliary lanes, ramp widening and adjusting the signal timings at the traffic signal controlling the off-ramp traffic. As it was mentioned in Chapter 2, field observations indicate that even if the queues of exiting vehicles are in the right-most auxiliary lane, the capacity of the freeway is reduced because drivers reduce their speeds when they see the queues of exiting vehicles.

4.3 Low-Cost Improvement Measures

Table 4.1 below shows a matrix of common bottleneck causes to potential low-cost improvement measures based on the findings from the review of the literature and the interviews with operating agencies.

Table 4.1 Mapping Bottleneck Types to Mitigation Measures

Bottleneck Types	**Mitigation Measures**											
	Auxiliary Lanes	Collector- Distributor Rd.	Paved Right Shoulder	Paved Left Shoulder	Shoulder / Plus Lane	Re-Stripping to add more, narrower lanes	All-Purpose Lane (concurrent or reversible)	HOV Lanes, (Concurrent or Reversible)	Truck Restrictions	Ramp Metering	Temporary Ramp Closures	Traffic Diversion Information
(I) Heavy on-Ramp Demand	++	-	+	-	++	+	++	-	+	++	-	+
(II) Lane Drops	++	-	++	-	++	++	++	++	+	+	+	+
(II) Tunnels and Bridges	-	-	-	-	-	++	-	+	++	-	-	+
(II) Horizontal & Vertical Curves	++	-	++	++	++	-	++	+	++	+	+	+
(II) Narrow Lanes and Lateral Obstruction	+	+	+	+	+	-	+	+	++	+	+	+
(II) Inadequate Accel. and/or Decel. lanes	++	++	++	-	++	+	+	+	++	+	++	++
(III) Weaving Sections	+	+	+	+	+	++	++	++	+	-	-	+

++ = good solution, + may be helpful, - = not helpful

It is clear that this there is not a simple one-to-one relationship between bottleneck types and mitigations. For example, ramp metering may be of greater benefit when a) there is sufficient storage length on the ramps so queuing on-ramp vehicles do not spill back on the arterial street system, and b) there are parallel routes that can be used by short trips. Traffic diversion information (static or dynamic) is a useful strategy when reasonable alternative routes exist. Important considerations for developing and implementing bottleneck improvements include cost-effectiveness, system-wide impacts and institutional issues.

The selection of the mitigation measure(s) should be based on careful analysis of alternatives and the cost-effectiveness of the proposed mitigations particularly if multiple bottlenecks are present. This is illustrated for the test section of I-680 freeway shown in Figure 2.2. The speed contour plot (Figure 2.3) provided initial guidance on locations to add auxiliary lanes to remove bottlenecks. Figure 4.1 shows the results from the evaluation of adding auxiliary lanes at selected segments of the study section. The horizontal axis in Figure 4.1 is the length of added auxiliary lanes in miles ("cost"). The vertical axis is the percentage reduction of total travel time (veh-hrs) for the freeway study section ("benefit"). The results show that the addition of auxiliary lanes on sections 28, (28+21), and (28+23) would produce the highest benefit/cost ratios. Note that the benefits from adding auxiliary lanes on sections (28+21) are about the same as adding auxiliary lanes on sections (28+25+23+21) at about one third of the cost.

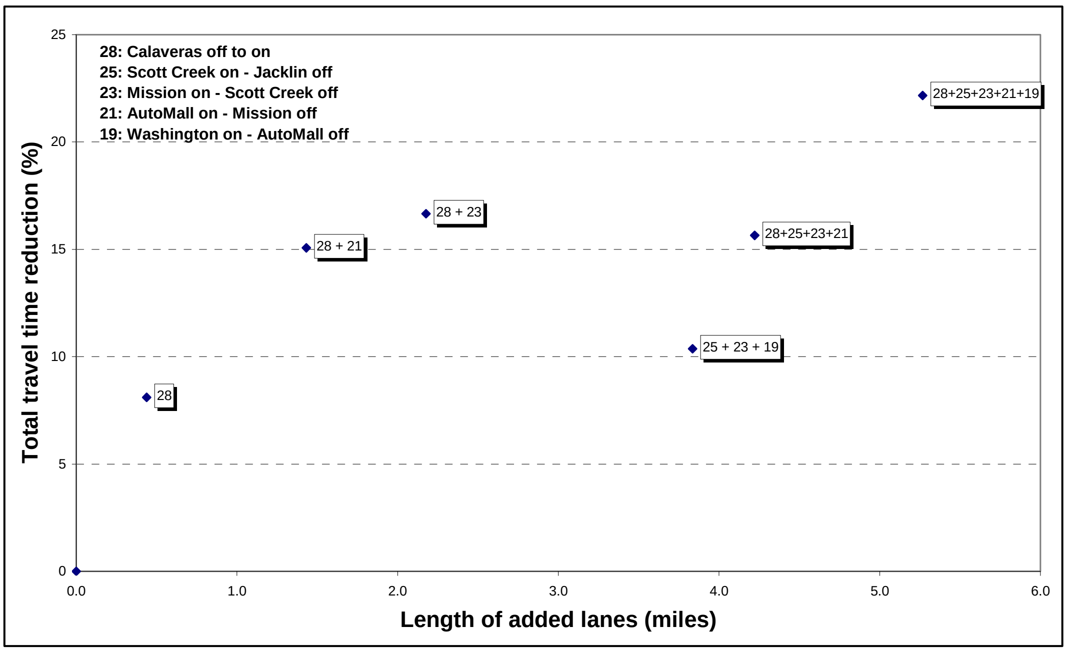


Figure 4.1 Comparison of Alternative Auxiliary Lane Configurations—I-680

The development of mitigation measures should carefully consider the system-wide impacts on the freeway under investigation, as well as how the measures will affect the adjacent network of highways and arterial streets. As it was discussed previously, removal of a bottleneck may expose another bottleneck elsewhere on the freeway (hidden bottlenecks). Hidden bottlenecks exist at freeway locations where the traffic demand exceeds the available capacity, but the demand cannot reach the hidden bottleneck location because of the presence of upstream or downstream primary bottleneck(s). In a number of cases primary bottlenecks "meter" the traffic downstream and prevent system breakdown. Several of the interviewed agencies (MTC, Nevada DOT, and The Netherlands) reported that system-wide demand levels are the underlying cause of individual bottleneck occurrences, and that geographically limited bottleneck improvements often only move the bottleneck problem to another up or downstream location. The bottleneck improvements undertaken by these three agencies tend towards addressing the demand side of the congestion equation – improvements such as ramp metering and traveler information, specifically traffic diversion information.

4.4 Analysis Framework

Figure 4.2 below shows the proposed framework for analysis of recurrent freeway bottlenecks. The analysis framework depends on the availability of real-time data from surveillance systems , and whether the analysis is for existing or projected conditions. Each case shown in Figure 4.2 is discussed in the following sections.

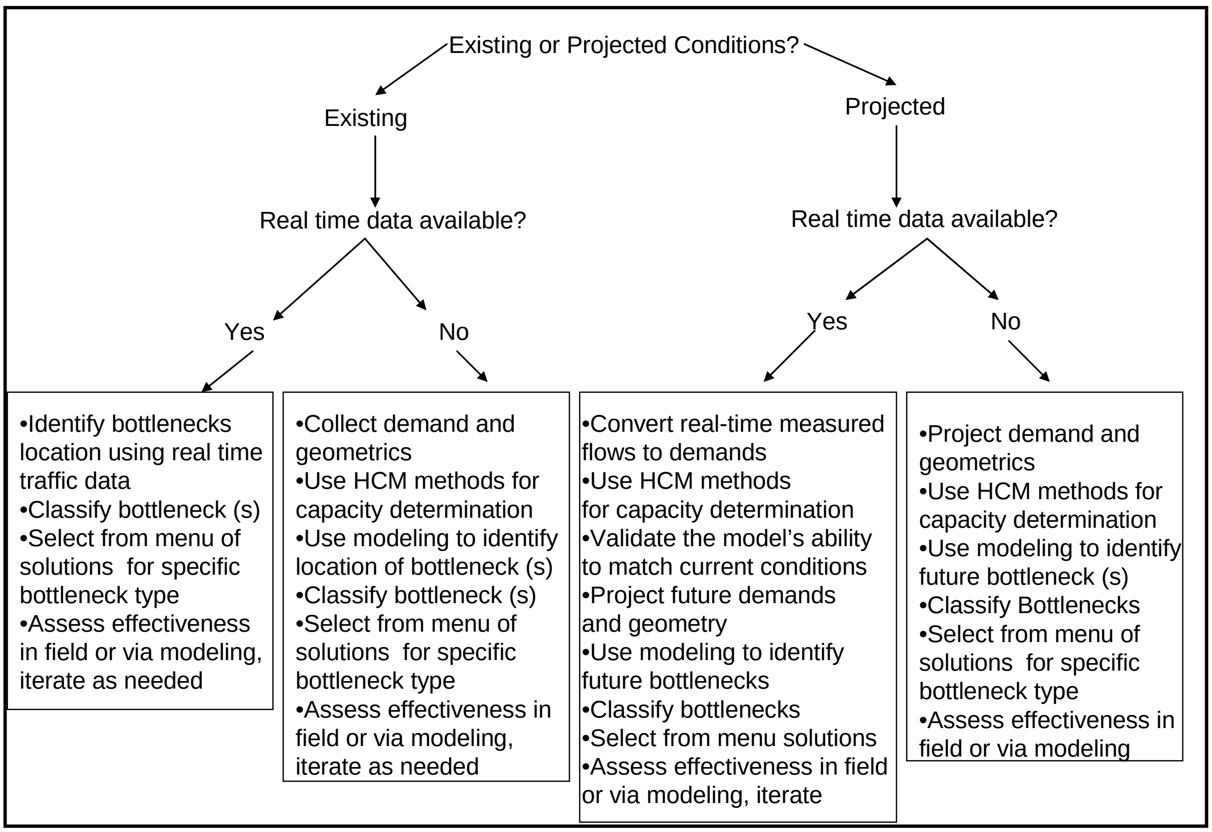


Figure 4.2 Bottleneck Analysis Framework

Note that in all cases, the assessment of the proposed solutions and the selection of the preferred mitigation measure(s) involves an iterative process based on a) the estimated benefits at the bottleneck location, b) costs of implementation, c) impacts to the freeway and arterial network, d) institutional constraints.

Case I: Existing Bottlenecks – Real Time Data Available

- Bottlenecks are identified based on the processing of the real time data (speeds, occupancies and flows) from successive loop detectors, according to the definition and the criteria described in Section 4.5.
- The cause of bottlenecks is determined next based on the freeway section geometrics at the bottleneck location and the pattern of flow breakdown based on the detector data (e.g., lane drops vs. on-ramp merges). Additional data that may be needed include control data such as ramp metering rates and HOV lane operations. As discussed previously such data are typically stored in the TMC database so no additional data collection effort is required.

- Appropriate low-cost solutions are selected based on the bottleneck type and the characteristics of the network.

Discussion

Real-time data cannot in general be used to assess the effectiveness of low-cost improvements prior to implementation; therefore, a modeling tool is required to assess the proposed improvements prior to field implementation. The modeling tool is also required to analyze possible hidden bottlenecks and the impacts to the freeway and arterial network. The real-time data are used to provide the input data to the analysis tool and performance data to calibrate the model to existing conditions prior to the analysis of the alternative scenarios. Figure 4.3 below illustrates the use of PeMS to calibrate a simulation model prior to the analysis of alternative scenarios along a section of I-210 freeway in Los Angeles (described in Section 5.3 –Case study 3). Comparison of the model predicted vs. measured densities expressed in veh/mile/lane (derived from the detector occupancies) indicates that the model reasonably replicates observed conditions along the freeway study section.

PeMS

		faulty	faulty				faulty					faulty	faulty	faulty	faulty			faulty	faulty			
	39.159	38.209	38.069	36.589	35.409	34.899	34.049	33.049	32.199	32.019	30.999	30.779	30.139	29.999	29.879	29.17	28.27	28.03	26.8	26.12	25.68	25.4
5:30 AM	36	24	29	22	26	26	22	24	25	26	25	21	-1	15	-1	19	19	17	-1	18	16	13
5:45 AM	47	29	37	21	26	27	24	27	25	27	28	24	-1	18	-1	23	25	22	-1	19	17	14
6:00 AM	40	34	39	26	32	30	27	36	29	31	29	26	-1	21	-1	24	26	24	-1	24	20	-1
6:15 AM	46	29	44	25	44	38	48	54	30	32	32	30	-1	23	-1	27	30	28	-1	31	25	-1
6:30 AM	59	37	45	49	58	51	47	66	29	31	32	30	-1	27	-1	29	30	30	-1	32	26	-1
6:45 AM	58	33	48	79	61	57	60	73	28	30	30	30	-1	28	-1	29	31	31	-1	33	28	-1
7:00 AM	62	32	54	98	69	63	70	76	27	30	33	42	-1	34	-1	30	31	33	-1	38	30	20
7:15 AM	67	44	69	88	72	61	67	74	32	45	57	49	-1	36	-1	34	48	51	-1	46	29	-1
7:30 AM	60	43	53	96	81	63	71	80	69	68	51	61	-1	32	-1	52	80	62	-1	-1	29	-1
7:45 AM	54	37	62	96	79	67	76	77	68	71	70	66	-1	49	-1	53	64	54	-1	41	31	-1
8:00 AM	58	34	60	88	82	68	79	86	63	67	56	65	-1	43	-1	45	72	61	-1	40	32	-1
8:15 AM	37	35	53	98	79	61	74	81	69	77	70	68	-1	35	-1	43	68	55	-1	36	30	-1
8:30 AM	53	31	60	96	79	72	74	77	68	71	61	61	-1	35	-1	34	68	53	-1	38	62	-1
8:45 AM	30	38	54	86	59	68	58	76	55	60	55	62	-1	42	-1	44	66	51	-1	38	-1	-1
9:00 AM	24	20	30	63	67	58	65	73	46	51	46	50	-1	39	-1	38	60	48	-1	36	-1	-1
9:15 AM	23	19	24	67	68	60	59	66	35	46	37	43	-1	32	-1	25	34	31	29	37	-1	-1
9:30 AM	24	14	24	29	83	52	66	66	28	44	40	41	-1	36	-1	26	27	28	48	35	-1	-1
9:45 AM	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
10:00 AM	24	18	22	14	23	22	34	57	23	26	25	25	-1	25	-1	22	23	23	-1	22	-1	15
10:15 AM	20	20	23	16	23	21	17	34	22	25	23	22	-1	22	-1	22	23	20	16	22	-1	15
10:30 AM	20	18	21	18	23	23	20	23	22	25	23	23	-1	21	-1	21	22	21	18	21	-1	15

	39.159	38.209	38.069	36.589	35.409	34.899	34.049	33.049	32.199	32.019	30.999	30.779	30.139	29.999	29.879	29.17	28.27	28.03	26.8	26.12	25.68	25.4
5:30 AM	29	27	29	22	25	26	26	25	25	26	25	27	26	27	22	20	20	21	20	21	18	15
5:45 AM	29	28	30	22	26	27	27	27	26	27	27	29	28	28	23	21	22	23	22	23	19	15
6:00 AM	31	31	33	24	29	30	30	39	28	30	29	31	31	32	27	24	25	26	25	26	22	17
6:15 AM	33	34	36	35	44	44	52	53	29	31	31	36	33	34	28	26	27	29	28	29	24	19
6:30 AM	37	51	54	84	61	58	61	53	28	31	43	45	33	34	29	27	28	30	29	30	25	21
6:45 AM	320	79	71	84	63	58	62	55	48	48	50	47	33	35	30	28	29	32	31	35	26	23
7:00 AM	592	71	64	81	65	61	64	59	57	49	52	48	37	35	31	28	33	41	42	37	26	21
7:15 AM	537	68	61	81	74	69	73	67	60	51	54	51	47	35	39	29	55	50	60	38	26	21
7:30 AM	346	74	66	90	76	70	74	66	60	51	56	53	53	41	54	63	70	59	64	39	26	21
7:45 AM	382	73	64	80	70	66	73	70	68	62	78	75	74	61	73	71	74	63	68	40	26	21
8:00 AM	128	54	57	84	81	77	85	82	76	68	82	79	78	64	75	73	75	64	68	40	26	22
8:15 AM	53	72	75	96	84	80	86	81	76	69	83	77	74	60	75	73	74	63	66	39	26	22
8:30 AM	194	82	74	89	81	78	83	78	73	66	79	75	70	57	70	68	68	57	62	39	26	23
8:45 AM	65	77	69	89	77	74	78	71	63	56	64	58	57	45	62	61	63	53	60	39	26	22
9:00 AM	27	74	70	80	61	56	61	56	44	43	51	46	41	38	55	56	57	48	57	38	26	22
9:15 AM	25	24	28	62	55	52	58	54	28	30	45	46	32	34	29	36	53	46	55	38	26	21
9:30 AM	28	25	28	21	56	52	58	55	28	30	32	39	32	33	28	25	29	33	39	34	26	21
9:45 AM	28	25	28	22	41	42	57	53	28	30	30	32	31	32	28	25	26	28	26	26	22	17
10:00 AM	26	24	26	22	25	27	38	54	28	30	29	32	30	31	26	24	25	27	26	26	22	18
10:15 AM	22	20	22	18	23	24	25	27	26	28	27	30	29	30	26	23	25	26	25	25	22	18
10:30 AM	21	20	22	18	22	24	24	24	23	25	24	27	26	27	23	21	22	24	23	24	20	16

Model

Figure 4.3 Measured vs. Predicted Density Contours—I-210

Real-time data can be used to evaluate the effectiveness of bottleneck improvements following their field implementation ("before" and "after" studies). Figure 4.4 shows the total delay to the freeway mainline (veh-hr) on an 8 mile section of I-8 freeway in San Diego, California, during the afternoon peak for a five year period. Delay is defined as the additional time to travel the section at speeds below 35 mph, and is calculated from the detector data. It can be seen that the delay is increasing due to the continuous traffic growth along the study corridor. A new ramp metering strategy was implemented in the corridor in

November of 2004. The data show that the delay on the freeway mainline was reduced by more than 50% indicating that the selected mitigation measure is effective in managing congestion.

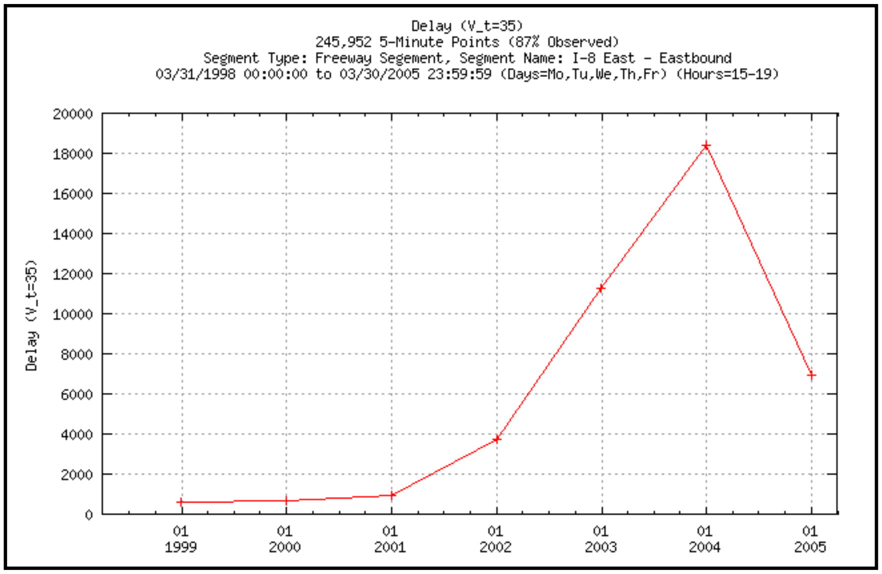


Figure 4.4 Assessment of Ramp Metering Based on Real-Time Data (I-8 E)

Case II: Existing Bottlenecks – No Real Time Data Available

- Manual data collection is required to determine freeway geometrics, traffic demand, and control data. The data requirements and sources were described in the previous section.
- Data on traffic performance are collected through floating car runs equipped with in-vehicle data loggers (or laptop computers) to automatically record travel speeds. Floating car runs are typically made at 15 min intervals. The processing of the data produces speed contour plots (as illustrated in Figure 2.3) that show the location of bottlenecks and congestion patterns on the study section. The data also provide travel times between selected entry and exit points of the study section.
- The capacity of each homogeneous subsection is calculated based on the HCM2010 procedures
- A model is used to determine the bottleneck location(s), type and impacts. The model is calibrated (adjustment of the model parameters) based on the comparison of model predictions against field data on performance measures (e.g., speed contours and travel times).
- Appropriate low-cost solutions are selected based on the bottleneck type and the characteristics of the network.
- The evaluation of the proposed solutions is performed using the model predictions (prior to field implementation) or field data on traffic performance following the implementation of the selected measures ("before" and "after" data).

Discussion

It is important that the freeway entry and exit counts represent traffic demands. This requires that traffic at the origin section of the freeway section and at the on-ramps is free-flowing and not affected by queues spilling back from downstream section(s). Also, exit counts at the off-ramps and at the downstream end of the study section should not be affected by queue back-ups. However, the exit counts do not represent traffic demands because of congestion on the freeway mainline due to bottlenecks. Therefore, these counts have to be converted into traffic demands. This is usually accomplished through the use of scale factors to match the total origin counts to total destination demands. Next, the demands on each freeway segment and the origin-destination demands are calculated.

The purpose of the study is the analysis of recurrent freeway bottlenecks. Therefore, it is important that the travel demand and performance data are collected during days and time periods of the day that are without incidents (e.g., accidents, breakdowns, debris), inclement weather or other random events that affect the operation of the freeway section. Incident logs from the TMC or other sources should be checked to verify that no incidents were present during the data collection periods.

The findings from the application of modeling tools in the case study indicate that the determination of the bottleneck location and impacts should involve multiple model runs when microscopic simulation models are used. This is because microsimulation models are stochastic, i.e., use random numbers to generate driver/vehicle characteristics, and the model results vary under the same input data on freeway geometric and traffic demands.

Case III: Projected Bottlenecks – Real Time Data Available

This process of analysis for this Case is similar to the previous Case II (Existing bottlenecks with no real time data) with the following important differences:

- Traffic demands are estimated from the real-time count data, provided that the study boundaries have been properly established to avoid any congestion effects, as discussed previously.
- Data on traffic performance are obtained from the real-time data with no need to perform floating car runs.
- The model is calibrated based on the existing conditions using the real-time based performance data.
- The analysis is performed using projected data on traffic demands and geometrics.

Case IV: Projected Bottlenecks – No Real Time Data Available

This analysis steps in this Case is similar with Case II (existing bottlenecks with no real-time data) with the important difference that projected data on traffic demand and freeway geometrics are used. Projected traffic demand data can be obtained from person and vehicle origin-destination tables provided by four-step planning models used in regional studies, traffic impact studies for new developments or based on trends on traffic growth based on historical data. Projected data on freeway geometrics may involve modification of existing facilities or new facilities (e.g., proposed freeway interchange as part of land development).

4.5 Use of Real-Time Data in Bottleneck Analysis

The findings from the literature and the interviews with operating agencies indicate that there is an increasing use of real-time data from surveillance systems for freeway operational analysis and performance measurement. As it was discussed in Chapter 2, real-time data are continually available and can be readily used to analyze bottleneck and congestion patterns over time. However, use of real-time data for bottleneck analysis requires that the data are valid, and efficient data archival systems to store, process and analyze the data and provide useful information to the user.

Data from surveillance systems often are missing (e.g., broken loop detectors, communication failures) or have errors (zero or constant values). Therefore, the real-time data should be verified for accuracy using appropriate detector diagnostics [61] before further use for operational analysis. Also, real-time data per travel lane should be provided from closely spaced detectors. Data from sparsely located detectors are of limited value in determining the bottleneck location and cause. In this case, the detector data can be used to supplement the manual field data collection.

A number of real-time archival systems of surveillance data have been developed [62], with California PeMS being considered the largest and most comprehensive system. However, none of these systems include algorithms internally to automatically identify bottlenecks. In this project, we refined and implemented the bottleneck identification algorithm developed by members of the research team [20] inside the PeMS system. The purpose of this implementation was to facilitate bottleneck analysis and explore the implementation and computational issues so it can be successfully implemented to other real-time data archival systems.

Proposed Algorithm

PeMS runs the bottleneck identification algorithm every day. This algorithm attempts to identify bottlenecks on the freeway system at every detector (by "detector" we mean a set of mainline lane sensors in a single direction). At a high level, a bottleneck exists downstream of a particular detector when there is a persistent increase in speed between the current detector and the detector immediately downstream. In order to identify a bottleneck, the PeMS implementation steps through every detector on the freeway system and performs a number of checks [20]:

- There is an increase in speed of at least 20 mph between the current detector and the one immediately downstream.
- The speed at the current detector is less than 40 mph.
- The detectors are less than 3 miles apart.
- The speed increase persists for at least 5 out of any 7 contiguous 5-minute data points.

If all of these conditions are met then the algorithm declares that there is a bottleneck at this location that has been activated for all of the seven 5-minute time points (note that this is a form of smoothing). In reality, the bottleneck is between these two detectors – its exact location is not known. As a matter of simplicity, the algorithm identifies the bottleneck is at the detector where the speed has dropped. In other words, the detector identified is still inside of the bottleneck.

These thresholds were determined based on applications of bottleneck algorithm and comparisons of the results with field observations. The algorithm was applied to the freeway systems in San Diego and Sacramento regions in California (a total of 581 directional freeway miles with over 1,100 detector stations) using the PeMS data. Also, the results were confirmed through discussions with Caltrans personnel who are familiar with the local operational characteristics.

Implementation Issues

While the above set of thresholds might define the location of the bottleneck on a particular day, there are a number of operational details that need to be worked out to translate this to a useful on-line algorithm inside a data time data archival system like PeMS. There are two concerns that are slightly related. First, the activation time of recurrent bottlenecks varies slightly from day to day. On some days, a bottleneck may become active 7:00 am and on others may be activated at 6:50 am. In addition, depending on the type of bottleneck, they can move slightly from location to location. If it happens that there is a detector that is right in the middle of the area over which the bottleneck takes place then one some days it will be activated and on others it's neighboring detector will be activated. Hence there is a slight amount of noise in the location of a correctly identified recurrent bottleneck in terms of space and time. Second, there will be a number of traffic phenomena captured by the simple algorithm listed above. Anything that disturbs the traffic flow for a single day will look like a bottleneck, including incidents, law enforcement activities, special events, etc. Hence, there is a need to filter out incorrectly identified recurrent bottlenecks, or “single-day” bottlenecks.

Two mechanisms have been employed in order to solve these slightly related “noise” problems. First, for the starting time of a single recurrent bottleneck, the bottleneck is marked as “activated” for a shift. Three shifts are used: AM shift (5:00 – 10:00 am), noon shift (10:00 am - 3:00 pm), and PM shift (3:00 -8:00 pm). Activating a bottleneck for a shift instead of for a specific time point provides quite a bit of stability in the results. As a result, a bottleneck that starts at 7:00 am on one day and 7:10 am on another, will count as the same bottleneck on two different days. Second, for the problem of identifying the location of the same bottleneck that slightly shifts around as well as the issue of filtering out spurious events, we rely on the reporting methodology. Essentially this means that we allow users to sort bottlenecks by the number of days activated. When doing so, locations that have true recurrent bottlenecks will be placed at the top of the report. Any locations that have been activated by one-time events will be at the bottom. Hence users can quickly identify “true” bottleneck locations.

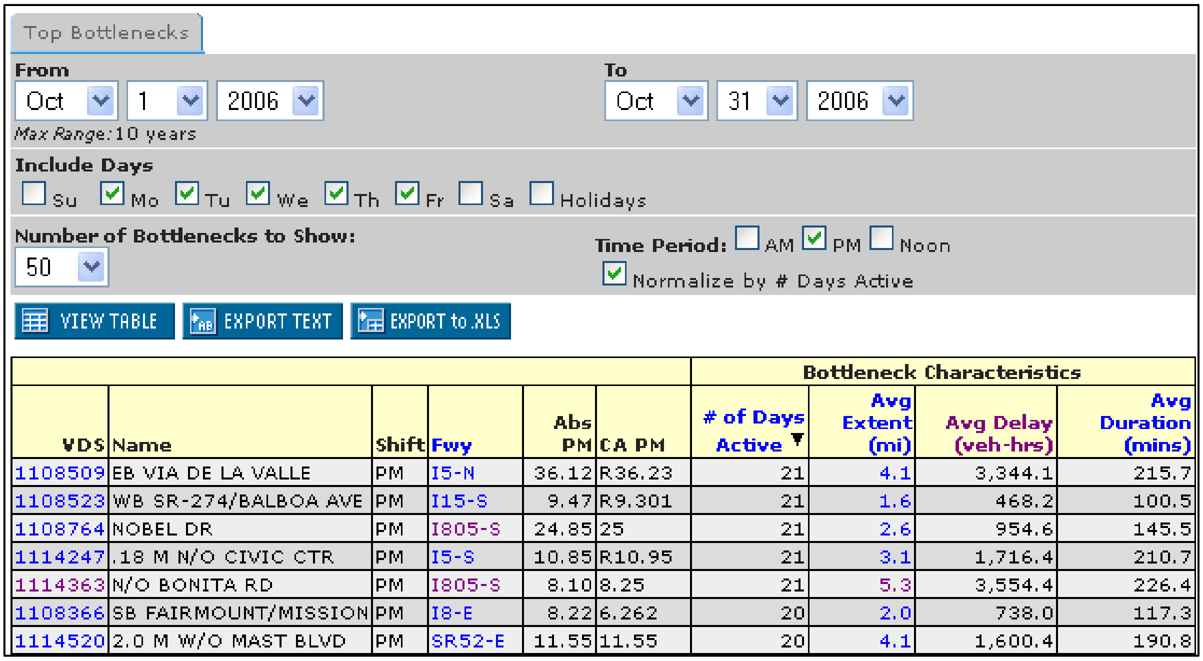
Performance Measures

For each location (detector) where a bottleneck is activated, PeMS computes and stores the following statistics for each analysis period (AM, noon and PM shifts).

- **Bottleneck duration**: How long the bottleneck was active during that particular shift on that day.
- **Bottleneck (spatial) extent**: For each 5-minute period when the bottleneck was active, the algorithm the algorithm locates the farthest upstream detector with speed less than 40 mph and uses that location as the extent during that 5-minute period. The median of the extents for each 5-minute period is used as the spatial extent measure for the entire bottleneck.
- **Bottleneck delay**: The delay is simply the sum of the individual segment delays for the entire duration and spatial extent of the bottleneck. The delay is computed as the additional time for all of the vehicles to pass each segment with respect to a threshold speed of 60 mph (which is assumed to be the average free-flow speed on the freeway mainline).

Note that one statistic that it is not captured explicitly is the starting and ending times of the bottleneck - the duration is captured not the starting time. Looking at how the starting time evolves over time might give an indication as to how demand is shifting over time. There are other reporting sections of the PeMS system that allow users to investigate this that aren’t related to the bottleneck effort. For example, the approximate start and end times that a bottleneck is active can be obtained from the speed or occupancy contour plots (Figure 2.6).

PeMS provides summary tables of the top bottlenecks in a region over a given time period sorted by the number of days activated, or any other available measure (Figure 4.5). The user selects the time range of interest and the specific analysis period (shift). The table lists out any detector station where a bottleneck was identified during the select days. Users can choose to sort the list according to the number of days that a bottleneck was identified at that site. For example, in Figure 4.5 the user has chosen to show bottlenecks only for the month of October, only on the weekdays, and only in the PM shift. Each line in the table is a detector where a bottleneck was activated. The table is sorted by the number of days that the bottleneck was activated. There are 22 weekdays in October but one of them is a holiday (Columbus Day). Hence for the 21 possible days, there are five locations where a bottleneck was activated on every day – clearly these are recurrent. The links in the table allow users to drill down to investigate additional aspects of the bottlenecks.



						Bottleneck Characteristics			
VDS	Name	Shift	Fwy	Abs PM	CA PM	# of Days Active	Avg Extent (mi)	Avg Delay (veh-hrs)	Avg Duration (mins)
1108509	EB VIA DE LA VALLE	PM	I5-N	36.12	R36.23	21	4.1	3,344.1	215.7
1108523	WB SR-274/BALBOA AVE	PM	I15-S	9.47	R9.301	21	1.6	468.2	100.5
1108764	NOBEL DR	PM	I805-S	24.85	25	21	2.6	954.6	145.5
1114247	.18 M N/O CIVIC CTR	PM	I5-S	10.85	R10.95	21	3.1	1,716.4	210.7
1114363	N/O BONITA RD	PM	I805-S	8.10	8.25	21	5.3	3,554.4	226.4
1108366	SB FAIRMOUNT/MISSION	PM	I8-E	8.22	6.262	20	2.0	738.0	117.3
1114520	2.0 M W/O MAST BLVD	PM	SR52-E	11.55	11.55	20	4.1	1,600.4	190.8

Figure 4.5 PeMS system: Table Listing Active Bottlenecks

PeMS also provides a "Bottleneck Map" (Figure 4.6). The bottleneck map shows users the location of the bottlenecks that have been identified by the algorithm. For the map view, users specify a date range and then a shift (AM, PM or Noon). The map shows the detectors where PeMS has identified a bottleneck during that time range and shift on any of those days. The size of the dot drawn for a detector is a function of the number of days that we saw the bottleneck at that location and the color is a function of the average spatial extent that the bottleneck stretched upstream.

When a user places the cursor over a bottleneck dot, PeMS pops up a tooltip box that provides more detailed information (as shown in Figure 4.6). If the user clicks on the dot then PeMS shows a contour plot that shows the speed over the day for the freeway.

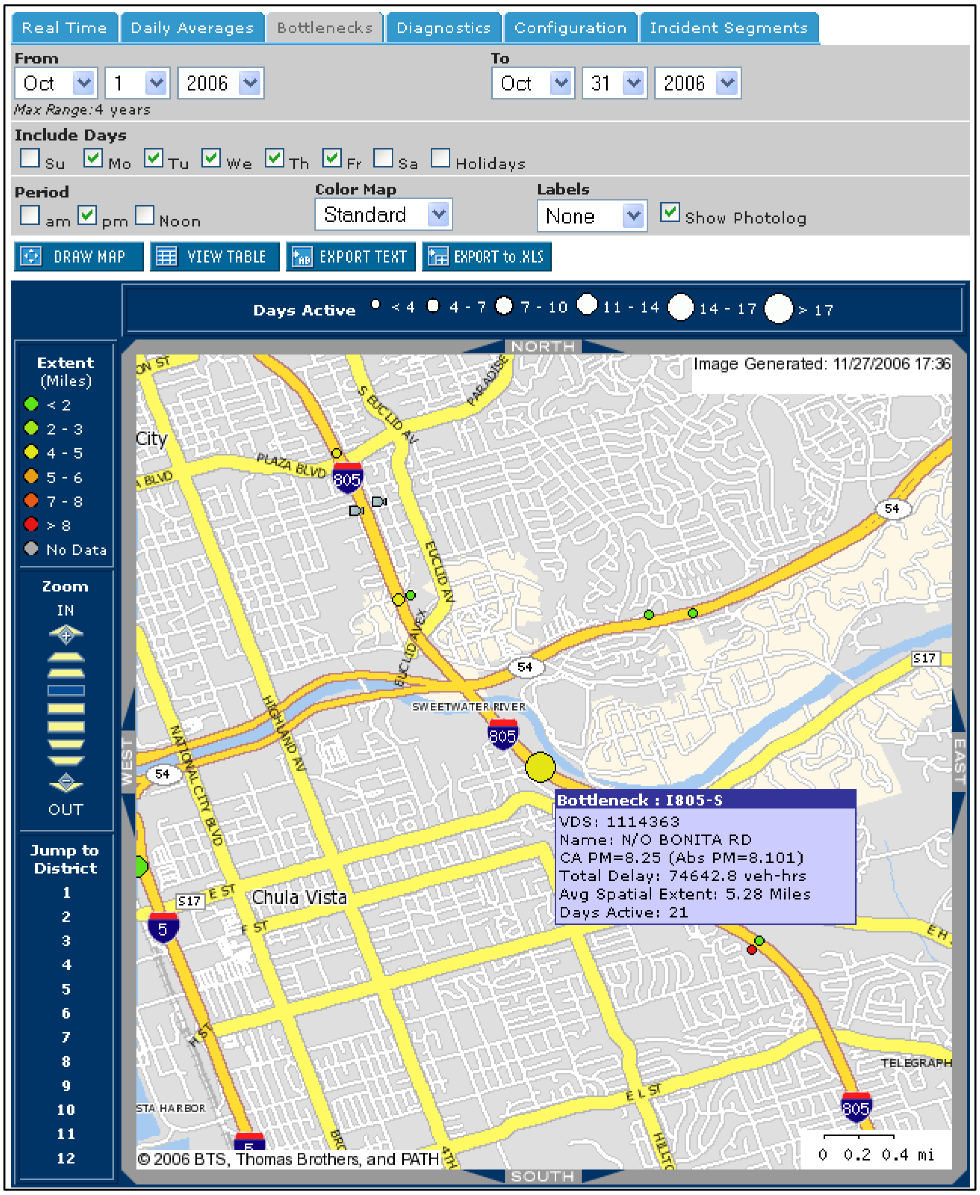


Figure 4.6 PeMS system: Map View of Bottleneck Locations

4.6 Use of Modeling Tools in Bottleneck Analysis

The findings from the literature review and interviews suggest that two factors can affect the choice of modeling techniques used when analyzing freeway bottlenecks. First, the perceived cause(s) of the freeway bottlenecks in question play an important role when selecting the proper modeling tool for further analysis. Type I bottlenecks (those caused by localized demand surges or by demand exceeding capacity system-wide) are caused by traffic conditions beyond the immediate location where the bottleneck itself may occur. These conditions are best analyzed using simulation models or other corridor-level analysis tools that can incorporate and measure the interactions between the multiple bottleneck locations and the traffic conditions on connected facilities. Type II bottlenecks (those caused by localized capacity constraints) may be most expediently analyzed using either (or a combination of) sketch planning tools and HCM methods. These techniques, when used in combination with field observations, can offer quick feedback to the analysts with a minimum of effort and resources required.

The second important factor affecting the choice of modeling techniques is the perspective of the analyst and his/her agency. MPOs like MTC in the San Francisco Bay Area with a "big picture", planning perspective on freeway bottlenecks may point to causes that are more system demand-driven, and prefer to use corridor-level, large scale simulation models capable of capturing the interactions between multiple bottleneck locations and system demand levels. Owner/operator agencies (State DOTs) like Caltrans District 4 are more likely to focus on geographically specific bottleneck locations and causes, and tend to favor a combination of field observations, sketch planning, and HCM type deterministic techniques for individual bottleneck locations analysis.

In reality, both perspectives and approaches are important – the system-based and the facility specific. Knowing which modeling approach to take depends on having some understanding of the underlying causes of a freeway bottleneck before the analysis has been undertaken. Knowing the underlying causes often requires having the results of a modeling analysis available. To transcend this "chicken and egg" problem, MTC and Caltrans District 4 have set course towards convergence of the macro and microscopic techniques. This convergence has been happening over the past few years and seems more the result of growing consensus and agreement between the individual staff involved, than by official policy directives conceived of and ordered by executive management. Both agencies are moving in the direction of corridor studies that will have the potential to analyze multiple bottleneck locations as well as the interactions between the freeways and parallel facilities and modes (e.g., frontage roads, arterials, and transit systems). At the same time, interviewed staff from both agencies independently emphasized the importance of using sketch planning tools in combination with field observations to develop "real-world" understanding of bottleneck conditions among their analysts. This combination of analysis approaches suggests a powerful strategy for systematic analysis and understanding of freeway bottleneck conditions, leading to both low-cost and effective mitigation measures to address them. First, by identifying bottleneck locations using facility specific tools, each location can be preliminarily classified as Type I, II, or III and using this classification, the most appropriate low-cost improvements can be selected and tested at the microscopic level of analysis where appropriate. The long-term viability and effectiveness of these low-cost solutions can then be tested using system based techniques (e.g., simulation models in conjunction with travel demand models) to determine how well they work within the context of the larger freeway and transportation system.

As it was discussed previously, when a freeway bottleneck is activated, we observe high density upstream of the bottleneck, and associated low flows and speeds, while downstream of the bottleneck high speeds and low densities are expected, unless another bottleneck is active further downstream. Model predictions on flow, density and speed on each segment of the network and other MOEs can be used to provide a definition for bottlenecks in the freeway system under study. However, thresholds of the particular performance measures need to be defined.

The thresholds for the model performance measures should be consistent with the findings from the literature and the experiences from the operating agencies. For example, average speeds upstream of the bottleneck of 35-40 mph or about 20 mph below the free-flow speeds. Also, we can set a threshold for a reduction in the vehicle flow following the bottleneck activation (in a range of 3-15% as reported in the literature). Such phenomena must be persistent, i.e., a minimum time duration that the bottleneck is active.

Based on the review of the literature and the judgment of the research team, the following criteria are proposed for identifying recurring bottlenecks using modeling tools:

- Downstream flow below capacity traveling at a minimum speed of 85% of the free-flow speed
- average vehicle speed of the segment at least 20 mph below the free-flow speed
- a minimum of 5% segment vehicle flow reduction from upstream segment vehicle flow
- three previous criteria sustained for at least 10 consecutive minutes in the same segment, and
- four previous criteria present for at least 40% of the simulation runs.

The last criterion is related to the application of stochastic models for bottleneck analysis, typically microscopic simulation models. These models generate driver/vehicle characteristics based on random numbers; therefore the model predictions vary on each simulation run under the same demand and supply input data. If the bottleneck is not activated among a significant proportion of randomly seeded simulation runs, then it is possible that the bottleneck is not a function of the roadway geometry and volumes. For these reasons a threshold of 40% was chosen. It is the judgment of the authors that if a bottleneck is occurring during at least 40% of the simulation runs (peak periods), that the frequency is great enough to warrant the designation of a bottleneck location.

These criteria are preliminary thresholds that may be adjusted as their consistency across different modeling tools is measured.

Selected Models

The following models were chosen in this study: FREEVAL Plus, CORSIM 5.1, and VISSIM 4.1. FREEVAL was selected because its model is based on the HCM2000 procedures that are widely used in freeway operational analyses. CORSIM and VISSIM were selected for the popularity as microsimulation software. In addition to their popular use, the nature of microsimulators allows for the analysis and evaluation of a wide range of mitigation measures, and the evaluation of their impacts on the freeway and the arterial street network. The selected models provide the performance measures necessary for bottleneck analyses: flows, densities and speeds per segment (link), at user specified time intervals. These models also provide estimates of VMT, VHT, travel time and delays for the assessment of mitigation measures.

As it was discussed in Chapter 2, FREEVAL is a macroscopic analysis tool developed North Carolina State University to implement the analysis procedures in Chapter 10 (Freeway Facilities) first introduced in HCM2000 [54],and updated with the analysis procedures in the 2010 edition of HCM. FREEVAL outputs include segment and facility d/c and v/c, space mean speed, and density contours for undersaturated as well as for congested freeway facilities. FREEVAL reports data for each freeway segment in user defined aggregated time intervals. The data, in conjunction with the speed, density, and volume to capacity graphs generated as part of the output, makes bottleneck identification, both active and hidden, rather straightforward.

CORridor SIMulation (CORSIM) is a microscopic stochastic simulation model, developed and maintained by FHWA, that has been in use for several decades by many public and private sector agencies. CORSIM is part of the Traffic Software Integrated System (TSIS) in order to make use of TSIS's graphical user's interface [63]. It contains two microscopic models: FRESIM for freeways and TRAF-NETSIM for arterial networks. For this study, only the microscopic freeway simulation model component (FRESIM) is considered. CORSIM is based on link-node network scheme where links represent homogeneous roadway segments and nodes mark a change in the roadway. Capacity related model parameters for freeway facilities include mean following headway, car following sensitivity factor, critical gap for lane changing, and minimum separation under stop-and-go conditions.

VISSIM is a microscopic simulator originally developed at the University of Karlsruhe in Germany in the 1970's and was commercially distributed beginning in 1993 by PTV Transworld AG [64]. VISSIM uses links to represent the network but it does use nodes; this non-traditional structure allows users the ability to better simulate geometric features and vehicle paths. VISSIM incorporates the Wiedemann psycho-physical driver behavior model for modeling car following and lane changing logic (65). Model parameters affecting freeway capacity include driver desired headway time, gap acceptance for lane changing and lateral behavior.

Hall et al [66] compared speed estimates from FREEVAL, INTEGRATION, CORSIM and FREQ models against field data at six oversaturated freeway facilities in North America and Europe. The results indicated that the HCM-based FREEVAL model was as good as and sometimes better than the simulation models in predicting freeway speeds under congested conditions. Bloomberg and Dale compared route-specific travel time and system travel time from the VISSIM and CORSIM models on congested networks [67]. Of the scenario comparisons, 33 of the 42 were within 20% of each other. The result trends were in agreement, however, VISSIM's results were generally more optimistic.

CHAPTER 5
CASE STUDIES

This Chapter describes case studies to illustrate the process of bottleneck analyses identified in the analysis framework shown in Figure 4.2. The four case studies described in this Chapter are based on real-world freeway analysis projects, selected from data sets already available to the research team and additional data sets identified in Tasks 1 and 2 of the project. The criteria used in the selection of the case studies included a) representation of a wide range of geometrics and traffic patterns, b) existence of bottleneck types commonly occurring the field, c) availability of real-time data, and d) data already coded into some (or all) of the selected analysis tools.

Case studies 1 and 2 are concerned with sites with existing bottlenecks where real-time data are not available. Case studies 3 and 4 represent sites with existing bottlenecks where real-time data are available. For each case study we describe in detail the definition of the study area boundaries, data collection and processing, bottleneck identification and classification, application of analysis tools, development and evaluation of improvements.

5.1 Case Study 1: I-270/I-44 Interchange (St. Louis, Missouri)

The freeway system analyzed in this case study is the interchange of I-270 and I-44 freeways southwest of St. Louis, Missouri (Figure 5.1). I-270 is part of a freeway loop around the city of St. Louis; at the location of its intersection with I-44 it has orientation of approximately NW to SE. I-44 runs approximately SW to NE; its Eastern end is in downtown St. Louis and it runs southwest and ends in Wichita Falls, Texas. Figure 5.2 displays each freeway direction with ramp labels and segment numbers. The freeway segments to be analyzed extend approximately 2.75 miles West and South of the interchange and approximately 2 miles North and East of the interchange. There is a collector-distributor road system along the western segments of I-44.

Northbound I-270: The NB section of I-270 is 5.58 miles long with 4 mainline lanes. It consists of 14 segments, which includes 3 off-ramp and 3 on-ramp segments. The remaining 8 segments are basic freeway segments. None of the ramp influence areas overlap and are all independent of each other.

Southbound I-270: The SB section of I-270 is 5.56 miles long with 4 mainline lanes. The section is made up of 13 segments, which includes 4 off-ramp and 2 on-ramp segments. The remaining segments are basic freeway segments. As with the Northbound direction, none of the ramp influence areas overlap and are all independent of each other.

Eastbound I-44: The EB leg of I-44 is 5.39 miles long with 13 segments. The section begins with 3 mainline lines and increases by one lane (corresponding on-ramp) at the 8th segment. There is a major weaving section at segment 5 and a ramp weave at segment 10. Segment 5 also contains a speed reduction area (bridge) that covers a majority of the segment. In addition to the two weaving segments, there are 2 off-ramp segments, 3 on-ramp segments, and 6 basic freeway segments. The influence area of the off-ramp of segment 6 extends 205 feet into segment 5.

Westbound I-44: The WB study section of I-44 is 5.45 miles long with 14 segments. The section begins with 4 mainline lanes and decreases by one lane (corresponding off-ramp) at the 4th segment, which is also a ramp weaving segment. There is a major weaving section without lane balance at segment 4, and a major weaving section with lane balance at segment 8. In addition to the two weaving segments, there are 2 off-ramp segments, 2 on-ramp segments, and 8 basic freeway segments. None of the ramp influence areas overlap and they are all independent of each other.

All segments on both I-44 and I-270 have a lane width of 12 feet, and average free-flow speed (FFS) of 65 mph. The proportion of trucks is approximately 4%. The two speed reduction areas mentioned above (I-44 EB segment 5 and I-44 WB segment 8) have a FFS of 50 mph.

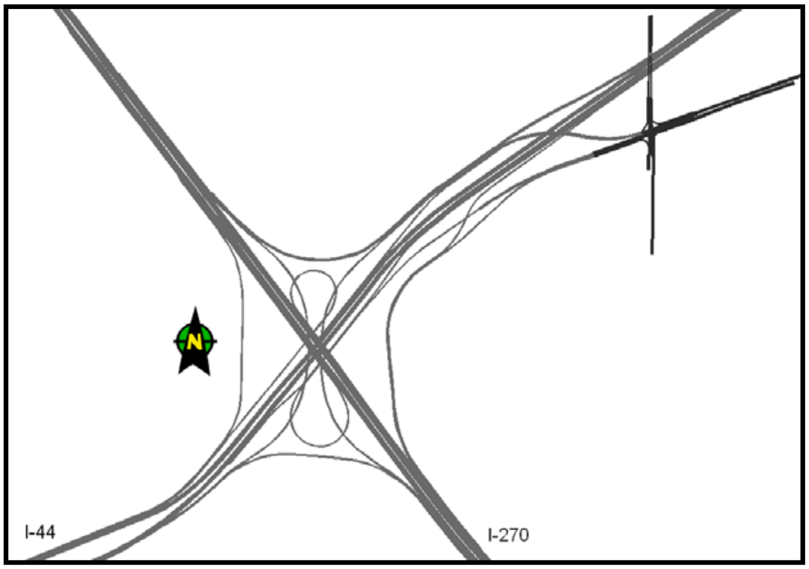


Figure 5.1 Case Study 1: I-270/I-44 Interchange, San Louis, Missouri

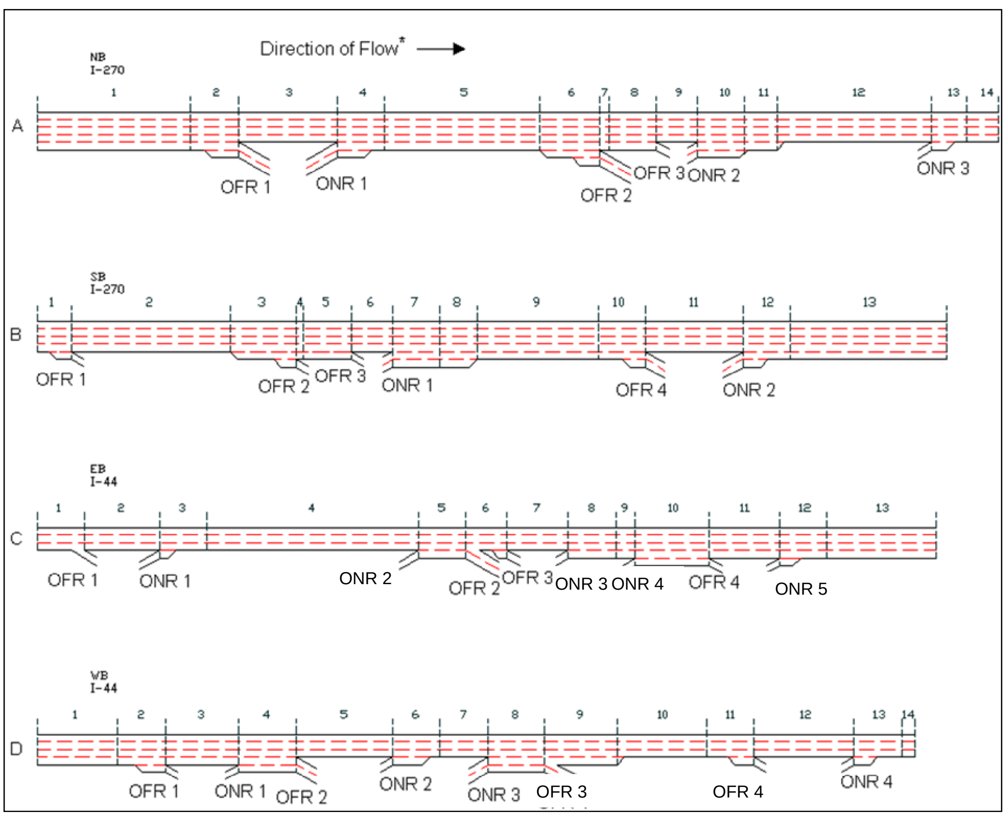


Figure 5.2: I-270/I-44 Study Area: Directional Lane and Ramp Configurations

Application of Selected Models

The study site was originally modeled using VISSIM for the Missouri Department of Transportation (MoDOT) by Crawford, Bunte, Brammeier (CBB) in 2003 [68]. Existing geometric and hourly traffic data for mainline I-270 and I-44 and all ramp movements were provided by MoDOT [68]. The origin/destination tables were based on traffic counts and weaving observations. These tables were input and modeled as vehicle paths as opposed to turning movement percentages to better reflect actual traffic patterns [68]. The FFS in VISSIM was expressed as a distribution with a median value of 62.3 mph.

The VISSIM model input and performance data was used as the baseline for the application of the CORSIM and FREEVAL models. Following the coding and verification of the input data to the models, the models were calibrated to ensure that they reasonably replicate existing field conditions. The calibration process for each model is discussed below:

VISSIM: Peak hour speed and queue length observations were performed for model calibration purposes, using floating cars. The baseline model was calibrated so that the modeled volumes on all segments generally fell within 5% or 50 vehicles of actual field volumes. Also the model parameters were adjusted so that the queue lengths and travel speeds reasonably replicated field conditions. From discussions with agency and consultant staff, it has been verified that the results of the VISSIM model were representative of the actual conditions of the modeled network. There were two bottlenecks that were communicated to the research team: the last on-ramp on I-270 NB (ONR 3 segment 13 in Figure 5.2A), and the weaving section on I-44 EB (segment 5 in Figure 5-2C).

FREEVAL: Because FREEVAL is a macrosimulation model, adjustments to driver behavior parameters are not possible. The only methods of calibration are changing ramp demands and segment capacity. The only adjustments to the FREEVAL model were made were to the ramp demands. The demands originally entered into FREEVAL were based on the origin-destination information provided with VISSIM. Also, FREEVAL only allows the input of a single free-flow speed (FFS) value; this was accounted for by taking the 50th percentile speed value from the VISSIM FFS distribution curve for the freeway mainline and for each ramp. The input FFS for the freeway mainline was entered as 62.3 mph into FREEVAL.

CORSIM: The first step in calibrating the CORSIM model was to verify that queuing was occurring at the same time and location as the queuing in the baseline VISSIM model. The results from initial CORSIM simulations showed the presence of an additional active bottleneck that was causing queuing upstream of the baseline active bottleneck on NB I-270. In order to rectify the discrepancy, adjustments were made to several CORSIM model parameters including: car-following sensitivity factors, mandatory lane change gap acceptance parameter, % of drivers desiring to yield the right-of-way to merging vehicles, multiplier for desire to make a discretionary lane change, and advantage threshold for discretionary lane change. Table 5.1 shows the default and calibrated parameter values. These values are applied to all vehicles for the entire simulation.

After the aforementioned adjustments were made, turn percentages and origin-destination assignments were adjusted in order for the ramp volumes in the CORSIM model to be more representative of those in the baseline VISSIM model. Figure 5.3 shows the total number of ramp vehicles per freeway direction serviced during the simulation for each model. The traffic volumes shown do not include the volumes in the first 15 minutes of simulation time. This is because during the first 15 minutes of simulation, the VISSIM model is still populating the network. So instead of the ramp volumes being a total for the entire 120 minute of simulation, the totals shown in Figure 5.3 are only the vehicles serviced by the ramps during the last 105 minutes.

Table 5.1 CORSIM Default and Calibrated Parameter Values

Model Parameter	Default Value	Calibrated Value
Car-following sensitivity factor for driver type 1	1.25	1.00
Car-following sensitivity factor for driver type 2	1.15	0.92
Car-following sensitivity factor for driver type 3	1.05	0.84
Car-following sensitivity factor for driver type 4	0.95	0.76
Car-following sensitivity factor for driver type 5	0.85	0.68
Car-following sensitivity factor for driver type 6	0.75	0.60
Car-following sensitivity factor for driver type 7	0.65	0.52
Car-following sensitivity factor for driver type 8	0.55	0.44
Car-following sensitivity factor for driver type 9	0.45	0.36
Car-following sensitivity factor for driver type 10	0.35	0.28
Mandatory lane change gap acceptance parameter	3	1
% of drivers desiring to yield right-of-way to lane-changing vehicles attempting to merge	20	50
Multiplier for desire to make a discretionary lane change	5	7
Advantage threshold for discretionary lane change	4	3

It can be seen that the ramp volumes from FREEVAL consistently better represent the baseline ramp volumes than the CORSIM model. This can be primarily attributed to two factors: first, the FREEVAL model does not evaluate the entire system, only one freeway directional section at a time. Because of this, vehicle balancing is not a forced parameter. Vehicle balancing is mostly responsible for the larger differences between CORSIM and VISSIM on the ONR3, OFR3, and OFR 4 segments of WB I-44 (Figure 5.3D). Second, the accuracy of FREEVAL is higher than it is in CORSIM. Ramp demand can be adjusted in the FREEVAL model to an accuracy of better than one vehicle. However, in CORSIM, the turn percentages and origin-destination assignments are done with whole percentages. In some cases this creates an accuracy as poor as to the nearest 27th vehicle for a 15 minute period on one ramp. This lack of accuracy, in conjunction with vehicle balancing, made the calibration of the CORSIM model much more cumbersome than the calibration of FREEVAL.

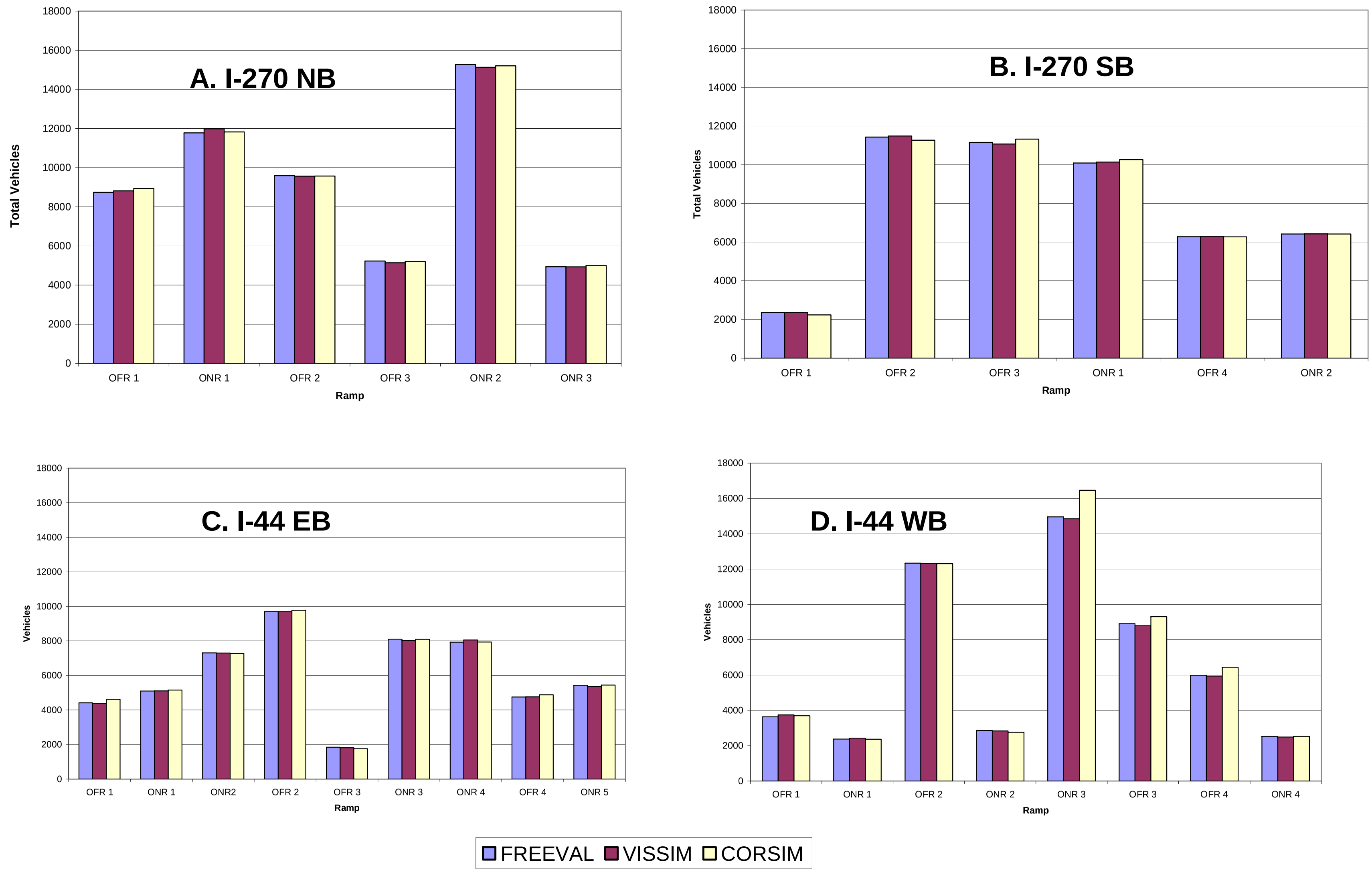


Figure 5.3 Predicted Ramp Volumes

Results—Baseline Conditions

Each model was run for eight 15-minute time periods. The first two time periods and last two periods were intended to model the shoulder periods. The third through sixth period used vehicle demands representative of the peak periods. The CORSIM and VISSIM microscopic models has been replicated 10 times (i.e., with the same input data but different random number seeds) to account for the stochasticity in the model results, according to the guidelines reported in the literature [59,67]. FREEVAL was run once, since it is a deterministic macrosimulation model, and the model results remain unchanged between model replications.

The average peak hour segment speeds predicted by each model on I-270 NB are shown in Figure 5.4. The average values plotted in the Figure were taken from the final three 15-minute periods of the peak hour. This rationale is similar to that used for totaling the vehicles serviced by the ramps. During the first 15 minutes, the system is populating with the peak volumes and therefore the values would be skewed if those values were included in the average.

The segment speeds from CORSIM and VISSIM were comparable, as it would be expected, with the driver behavior parameters and ramp volumes adjusted already. FREEVAL generated more dramatic speed and density curves. This can most likely be attributed to the macroscopic nature of the model. Because FREEVAL uses the speed density curves from HCM, the curves will not be smooth from segment to segment as they would with the microscopic simulators. The largest discrepancies between FREEVAL and the CORSIM/VISSIM microscopic models were in the performance of weaving sections.

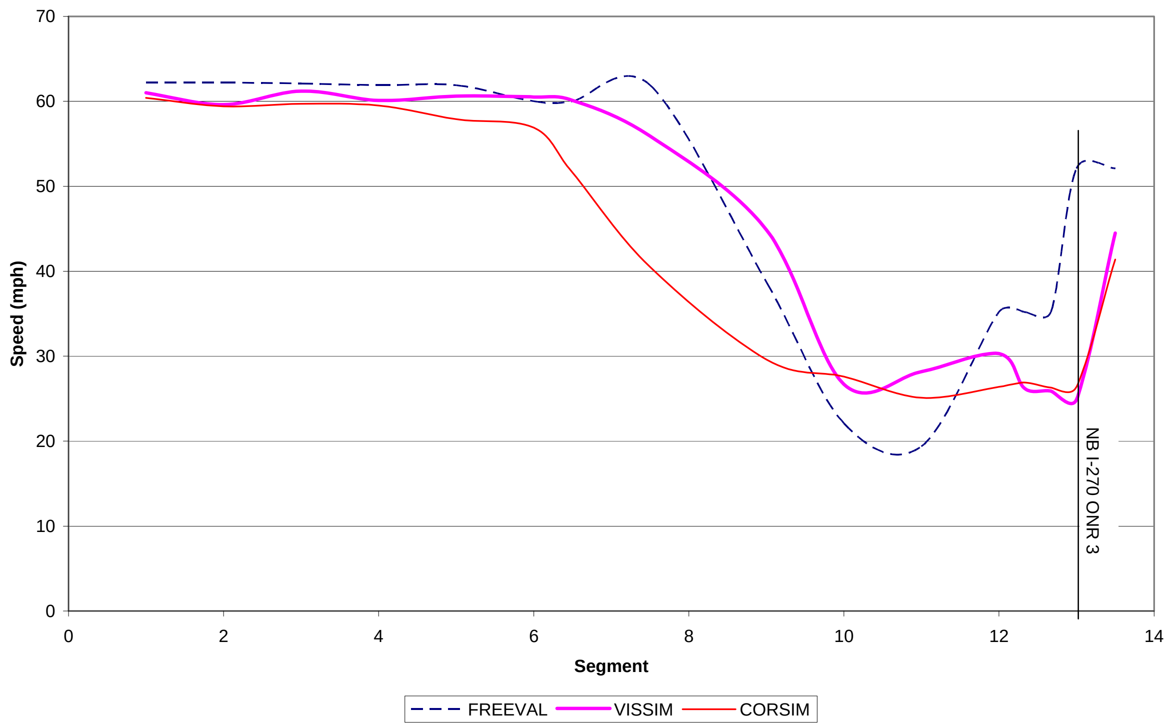


Figure 5.4 I-270 NB Average Peak Period Vehicle Speeds by Segment

Northbound I-270 Segment 13 (on-ramp merge): As can be inferred from Figure 5.4 there is an active bottleneck with associated queuing at the on-ramp segment 13 (ONR 3) on NB I-270 (Figure 5.2A). This is the same bottleneck communicated by the agency staff. This bottleneck is caused by a combination of high mainline traffic volume and the on-ramp traffic entering the freeway from Big Bend Rd. exceeding the capacity of the downstream freeway segment.

This bottleneck was active in all 10 of the VISSIM and CORSIM replications and in the FREEVAL model. Figure 5.5 shows the predicted speed profiles from VISSIM and FREEVAL at this location. The bottleneck activations occur at approximately the same time; in FREEVAL, in 9 of 10 of the VISSIM replications, and in CORSIM the bottleneck becomes active in time period 3. The bottleneck becomes active in 1 of 10 of the VISSIM replications in time period 4. The activation time appears to be longer in VISSIM than in FREEVAL by about one time period (15 minutes).

CORSIM and VISSIM predicted the lowest speeds and highest densities are in the merge area directly after the gore. The queuing in FREEVAL starts just upstream of the on-ramp in segment 12. The difference in bottleneck location between the models is to be expected since FREEVAL is macroscopic and will place the start location of the queuing at the on-ramp gore and CORSIM/VISSIM require the merge area to fail before queuing can begin.

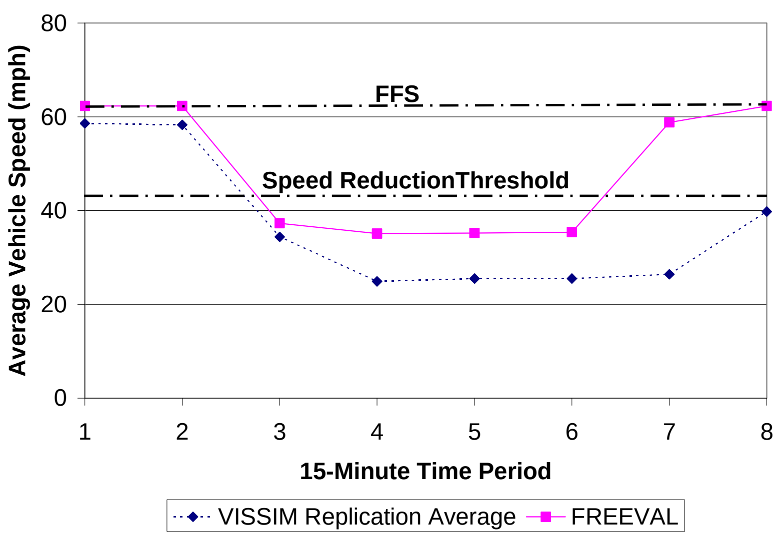


Figure 5.5 NB I-270 Segment 13 Speed Profile

Northbound I-270 Segment 10 (on-ramp merge): This segment is treated as a potential bottleneck that is hidden by queuing downstream caused by the active bottleneck in segment 13. Figure 5.6 shows the predicted speed profiles. The congestion is present in all VISSIM replications and the FREEVAL model.

This potential bottleneck is a combination of the lane drop in Segment 11 and the merging traffic from the on-ramp in Segment 10 (Figure 5.2A). The on-ramp in Segment 10 is a 2-lane ramp with 2 acceleration lanes. Because the 2nd acceleration lane doesn't drop within 1,500 feet of the on-ramp gore, it is treated as an on-ramp segment followed by a lane-drop segment. The two segments cover a distance of approximately 2,500 feet. Note that FREEVAL places the queue on the on-ramp because of a downstream queue and therefore a bottleneck doesn't show up on the mainline.

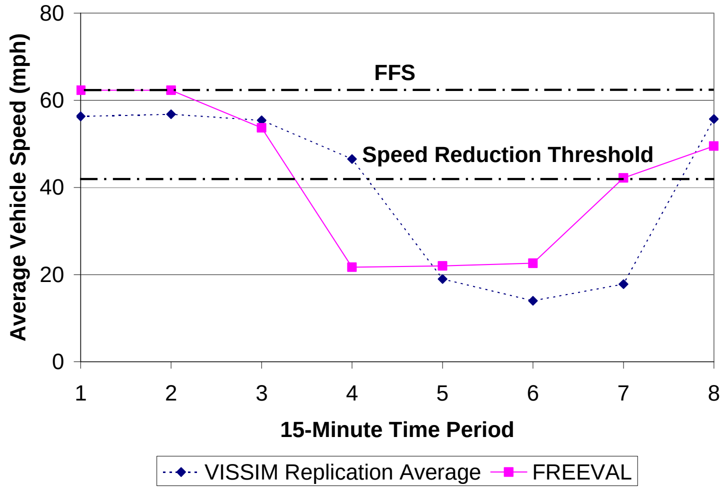


Figure 5.6 NB I-270 Segment 10 Speed Profile

Southbound I-270 Segment 3 (off-ramp diverge): The bottleneck at this location is caused by high off-ramp demand volume that exceeds the capacity of the off-ramp and causes spillback onto the freeway mainline. Figure 5.7 shows the predicted speed profiles at this segment. The bottleneck is active in 5 of 10 of the VISSIM replications. The bottleneck is not predicted in the FREEVAL model, because FREEVAL does not recognize off-ramp capacity limitations. Congestion at this segment was thought to be exacerbated and possibly caused by queuing in the right lane for the downstream off-ramp lane drop at segment 5 (Figure 5.2B). Therefore, bottleneck treatments are considered for both segments 3 and 5 on I-270 SB.

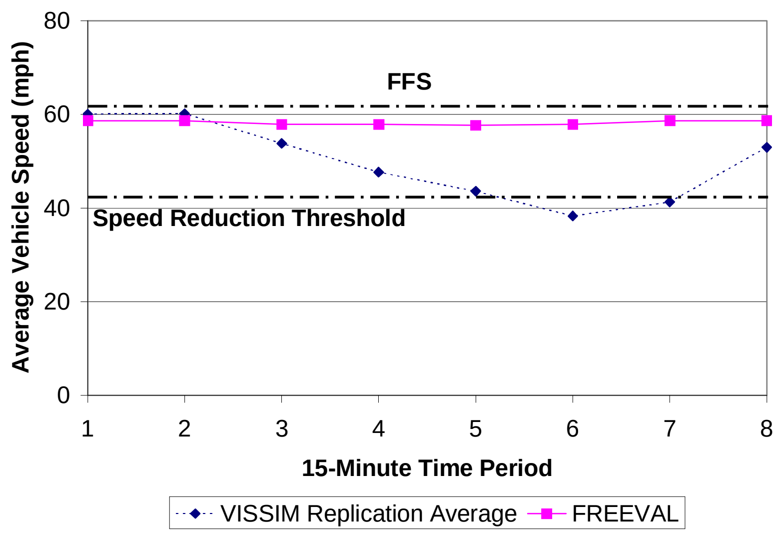


Figure 5.7 SB I-270 Segment 3 Speed Profile

The segment 5 off-ramp, a tight loop ramp, occurs in conjunction with a lane-drop. The exiting demand exceeds the capacity of the ramp and slowing and spillback is created on the right lane of the freeway. Also, because of the fairly close proximity of the ramps (~1,800'), vehicles desiring to exit at the downstream ramp, are often in the far right lane before the upstream ramp diverge. These vehicles reduce the available capacity of the lane and vehicles wishing to exit at the upstream ramp have a difficult time reaching the ramp if they have not moved into the right lane well upstream. When the queuing of the downstream ramp extends upstream to segment 3, it creates congestion and triggers bottleneck identification when using the pre-defined criteria.

Eastbound I-44 Segment 5 (weaving section with reduced FFS of 50 mph): This congested location is a major weaving section with lane balance along with a speed reduction zone (bridge deck) and narrow lanes (Figure 5.2C). While this segment's demand does not reach or exceed the capacity as calculated by the HCM, it does have a high weaving volume (>2,000 vphpl), and a moderate volume ratio (v_w/V = 0.34). This bottleneck is caused by congestion at the off-ramp of the weaving section. The off-ramp feeds into the on-ramp at segment 10 of NB I-270, which was discussed previously.

Tables 5.2 and 5.3 show the predicted speeds and densities per 15 min time interval (t_1 through t_8) from the FREEVAL and VISSIM model (10 replications). No bottleneck was identified at this location in any of the CORSIM replications. Based on the proposed bottleneck definition, only VISSIM predicts the presence of a bottleneck at this segment 70% of the time (7 of 10 replications). The bottleneck does not always activate in the same time period in the VISSIM model. The bottleneck does not appear in FREEVAL because of its limitations in modeling facility interactions and off-ramp capacity.

Table 5.2 I-44 EB Segment 5 Speeds (mph)

Simulation	t_1	t_2	t_3	t_4	t_5	t_6	t_7	t_8
FREEVAL	44.1	44.1	41.1	40.9	41.2	41.0	44.1	44.1
VISSIM 1	48.1	48.3	46.1	46.1	45.4	19.9	11.3	17.6
VISSIM 2	48.6	48.1	46.0	44.0	44.4	45.2	48.2	47.9
VISSIM 3	47.6	47.8	45.5	45.1	45.3	26.5	10.7	14.1
VISSIM 4	47.6	48.3	46.3	45.7	45.6	45.4	47.6	48.1
VISSIM 5	48.6	48.1	46.5	45.9	46.3	33.7	20.1	34.8
VISSIM 6	48.2	47.8	45.7	46.3	44.5	31.6	13.4	15.7
VISSIM 7	48.1	48.1	46.6	45.5	33.1	13.4	12.9	20.8
VISSIM 8	48.3	48.3	46.6	44.1	45.7	27.7	16.5	43.6
VISSIM 9	48.4	47.7	46.6	46.3	46.2	43.7	28.5	48.4
VISSIM 10	48.1	47.9	45.9	46.1	46.1	46.1	47.2	48.3

	45-50 mph
	40-45 mph
	30-40 mph
	20-30 mph
	10-20 mph
	0-10 mph

Table 5.3 I-44 EB Segment 5 Densities (vpmpl)

Simulation	t_1	t_2	t_3	t_4	t_5	t_6	t_7	t_8
FREEVAL	22.9	22.9	36.8	37.5	35.9	37.3	22.9	22.9
VISSIM 1	18.1	21.4	30.8	33.9	34.2	93.9	157.4	108.5
VISSIM 2	17.3	21.1	31.7	35.9	35.9	34.0	22.5	21.2
VISSIM 3	18.2	21.0	33.1	33.6	34.8	63.0	154.2	120.1
VISSIM 4	18.8	20.8	31.0	33.8	34.7	33.9	23.6	20.5
VISSIM 5	16.9	21.5	32.2	32.8	31.2	49.5	117.1	35.3
VISSIM 6	17.9	21.5	31.8	32.3	36.2	50.9	151.6	120.4
VISSIM 7	18.3	20.9	31.0	33.4	50.2	134.7	148.7	93.9
VISSIM 8	17.7	21.2	30.2	36.9	33.5	61.5	126.6	25.9
VISSIM 9	17.8	21.5	31.0	32.3	32.2	36.8	61.9	21.0
VISSIM 10	18.1	20.9	32.1	33.5	33.6	32.8	22.9	21.9

	0-10 vpmpl
	10-20 vpmpl
	20-28 vpmpl
	28-35 vpmpl
	35-43 vpmpl
	>43 vpmpl

After the above described modeling efforts with all three models, and discussions among the study team it was decided that only FREEVAL and VISSIM would be further pursued for several reasons. VISSIM and CORSIM produced similar results and is felt that a single representative micro simulator would be sufficient to carry out one of the study objectives, namely contrasting different classes of modeling tools. Also, two additional cases studies (Case studies 3 and 4) were already coded into the VISSIM model.

Sensitivity Analysis

A sensitivity analysis was performed to test the sensitivity of previously defined criteria for bottleneck identification using the simulation tools. The origin-destination demands were adjusted to 90, 110, and 120 percent of the baseline conditions. As with the baseline model, each of the adjusted traffic volume scenarios were replicated 10 times with different random number seeds in VISSIM, and once in the macroscopic deterministic FREEVAL model. The results are shown in Tables 5.4 and 5.5.

Northbound I-270 Segment 13 (ONR): As shown in Table 5.4 even when the traffic volumes are reduced to 90% of the baseline volumes, the bottleneck is activated in 9 of the 10 replications of VISSIM model. However, FREEVAL does not predict a bottleneck when the traffic volumes are reduced because the resulting bottleneck demand to capacity ratio (d/c) is less than 1.0 and no queuing takes place.

Northbound I-270 Segment 10 (ONR): As it was previously mentioned this is a potential hidden bottleneck, which is often exacerbated by the downstream queuing because of the active bottleneck in Segment 13. This likely interactivity is most likely the cause for the high sensitivity to traffic demands, demonstrated by the difference in bottleneck occurrences in Table 5.5.

Southbound I-270 Segment 3 (OFR): When the queuing of the downstream ramp extends upstream to segment 3, it creates congestion and triggers bottleneck activation based on the pre-defined criteria. While delay on segment 5 occurs in all baseline VISSIM replications, it only creates active bottleneck conditions at segment 3 in half of the baseline replications (Table 5.4). The reason that the bottleneck is not predicted in FREEVAL is because it cannot handle lane-by-lane analysis, and off-ramp capacity.

Eastbound I-44 Segment 5 (Weaving): VISSIM predicts a bottleneck in 7/10 of the replications with baseline traffic volumes and all replications for increased traffic volume scenarios. FREEVAL only predicts an active bottleneck when the traffic volumes are increased to 120% of the baseline conditions.

Table 5.4 Sensitivity of Predictions to Traffic Demand--VISSIM Model

	Bottleneck Section			
Traffic Level (%)	**NB I-270 Seg 13**	**NB I-270 Seg 10**	**SB I-270 Seg 3**	**EB I-44 Seg 5**
90	9/10	0/10	0/10	0/10
100 (Baseline)	10/10	10/10	5/10	7/10
110	10/10	10/10	10/10	10/10
120	10/10	10/10	10/10	10/10

Table 5.5 Sensitivity of Predictions to Traffic Demand--FREEVAL Model

	Bottleneck Section			
Traffic Level (%)	**NB I-270 Seg 13**	**NB I-270 Seg 10**	**SB I-270 Seg 3**	**EB I-44 Seg 5**
90	0/1	0/1	0/1	0/1
100 (Baseline)	1/1	0/1	0/1	0/1
110	1/1	1/1	0/1	0/1
120	1/1	1/1	0/1	1/1

The sensitivity analysis has shown that VISSIM is not highly sensitive to low to moderate changes in traffic volumes. Incremental increases in traffic demands did not create large differences in the frequency of bottleneck activations in the model. The sensitivity analysis results do not seem to reveal much about FREEVAL. The segment with the known bottleneck, NB I-270 segment 13, no longer activates when the volume is reduced. However, at the 3 sites that do not show congestion under baseline conditions, SB I-270 segment 3, EB I-44 segment 5, and WB I-44 segment 4, when traffic was added, only one of the segments predicted an active bottleneck. Based on the results, it does not seem that the model is extremely sensitive.

Bottleneck Improvements

The following bottleneck improvements were modeled and evaluated for the bottlenecks identified at the study site:

- Auxiliary lane addition
- Restriping and lane-narrowing in conjunction with plus-lane
- Fixed-time ramp metering
- Off-ramp widening

Northbound I-270 Segment 13 (on-ramp merge): The treatment applied at this bottleneck location was the addition of an auxiliary lane extending to the following downstream off ramp. The original condition is shown in Figure 5.8A with the auxiliary lane treatment shown in Figure 5.8B. Because the ramps are approximately 3,600 ft apart, the addition of the auxiliary lane would not create a weaving segment by HCM standards. Therefore, adding the downstream off-ramp to the model is not necessary. While the construction of an additional lane is perhaps not a low-cost solution, it will provide a comparison of conditions if a lane was simply added.

FREEVAL and VISSIM predicted that the additional capacity removed the bottleneck and vehicles traveled near or at free-flow speed. It is worth noting, the congestion in segment 5 (weaving section) of EB I-44 is removed through this treatment in the VISSIM model. So while this represented a more expensive treatment, the additional capacity removed congestion on two different freeways.

Next, restriping and plus lane was tested (Figure 5.8C). The restriping and plus lane were implemented starting approximately 1,000 feet upstream of the segment 13 on-ramp gore. Trucks are prohibited to access the plus lane. In VISSIM, this treatment was modeled by narrowing the lanes, adding speed reduction zones based on the lane width adjustment factor for calculating FFS in the HCM [3], and adding pre-timed signals in the added left lane spaced approximately 25' apart to simulate lane control signals. The VISSIM results showed significant delay reduction but the bottleneck remains active in all model replications; however, it did remove the congestion upstream on NB I-270 segment 10 and the recurring bottleneck on segment 5 of EB I-44. The treatment did remove the bottleneck in FREEVAL.

Finally, fixed-time ramp metering was modeled in VISSIM and FREEVAL for during the peak period and the following 15-minute period. The metering rates were set to allow the queue created to dissipate before the meter was turned off as well as not spill back onto the surface streets. The meters on the ramp were placed to allow appropriate acceleration distance as outlined by the AASHTO Green Book [2]. Metering did reduce the delays on the freeway mainline, however the bottleneck remained active in 9 of 10 VISSIM replications and in the FREEVAL model. This indicates that the ramp and mainline demands of the segment are too high to be treated by ramp metering alone without creating severe congestion on the surface streets. However, ramp metering did remove the congestion upstream at NB I-270 segment 10 and the recurring bottleneck at segment 5 on EB I-44.

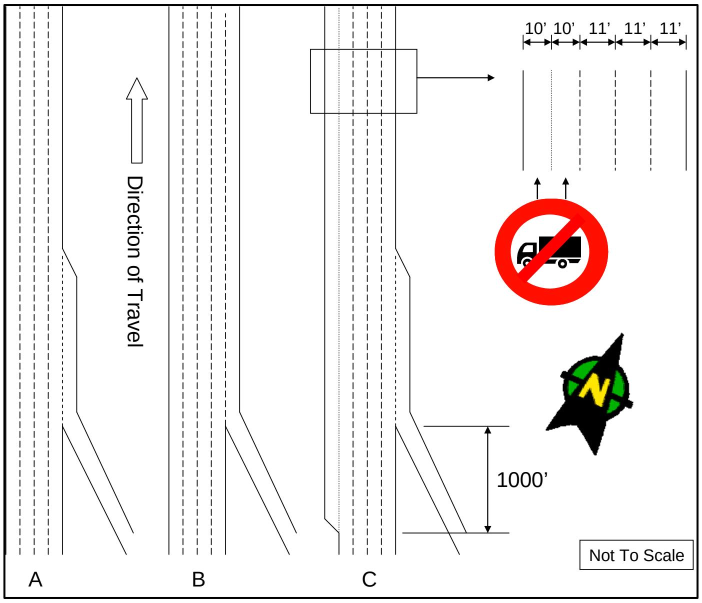


Figure 5.8 NB I-270 Segment 13 Bottleneck Treatments

Northbound I-270 Segments 10 (on-ramp merge): The congestion at this location was removed after the improvements at the downstream bottleneck at segment 13 (addition of the auxiliary ramp downstream and the restriping and plus-lane treatment, and ramp metering) in both FREEVAL and VISSIM. Since this bottleneck did not activate once the downstream bottleneck was removed, this segment is not by definition a recurring "hidden" bottleneck under baseline conditions.

Southbound I-270 Segment 3 (off-ramp diverge): Congestion at this segment was thought to be exacerbated and possible caused by queuing in the right lane for the downstream off-ramp lane drop at segment 5. Because of this, the off-ramp at segment 5 was widened to two lanes in order to make storage room on the ramp to avoid spillback onto the freeway as shown in Figure 5.9. While the desired results were achieved at the segment 5 off-ramp lane drop, the analysis shows that the treatment did not alleviate the bottleneck at segment 3, as it was activated in 6 of 10 VISSIM replications.

The segment 3 off-ramp was expanded to a 2 lane off ramp and the results show that this treatment removed the bottleneck at this location. The baseline and treated conditions are shown in Figure 5.10. The far right lane of the freeway is an exit only lane and the 2nd lane was converted to a through-exit lane. Therefore, the only additional construction necessary would be the widening of the ramp. However, since the paved area of the ramp is approximately 30' wide, it might be possible to restripe and achieve the same results without additional construction.

Eastbound I-44 Segment 5 (weaving section): The congestion at this segment was shown to be eliminated completely. This recurring bottleneck was created by congestion elsewhere on the network, so once that was treated, the bottleneck was removed. Ramp metering at this segment's on-ramp did not remove the bottleneck at this location; the bottleneck was still active at this segment in 4 of 10 VISSIM model replications. However, since it is only active in 40% of the replications, it does not qualify as a recurring bottleneck location.

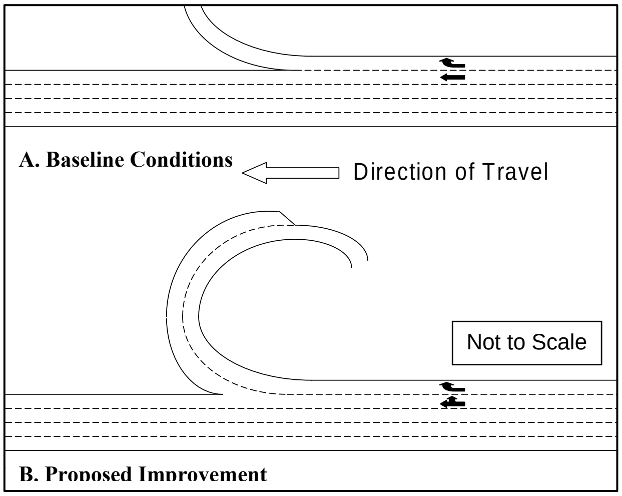


Figure 5.9 SB I-270 Segment 5

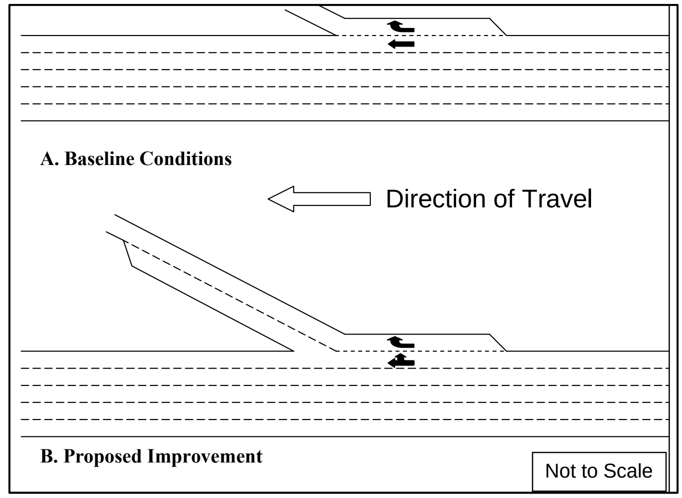


Figure 5.10 SB I-270 Segment 3

Summary of the Results

The only confirmed bottleneck reported to the research team was on NB I-270 segment 13 (Figure 5.5). All models predicted bottleneck activations at this location. VISSIM predicted two other bottleneck locations on SB I-270 segment 3 (Figure 5.7) and EB I-44 segment 5 (Tables 5.2 and 5.3), and possibly a hidden bottleneck on NB I-270 segment 10 (Figure 5.6). Discussions with the modeling staff of the original study for MoDOT confirmed congested conditions at the two NB I-270 locations (segments 13 and 10) and the EB I-44 location (segment 5), but not on segment 3 of SB I-270. The assertion is that segment 13 of NB I-270 was the only true bottleneck and that the congestion at segment 10 of NB I-270 and at segment 5 of EB I-44 were caused by queues extending upstream on the through lanes as well as the ramp connecting the two freeways.

The FREEVAL and VISSIM models did not produce the same results regarding bottleneck conditions on the test site. This is caused by limitations of the models; most notably the inability for FREEVAL to a) explicitly model multiple freeway facility interactions and b) recognize capacity constraints at the off-ramps. The sensitivity analysis in most cases confirmed the presence or absence of a bottleneck under the baseline condition. However, there were large differences in the propensity of detecting bottlenecks between the macroscopic and microscopic analysis tools. For example, only 6 of the 20 experiments (30%) with FREEVAL resulted in identifying a bottleneck, while 13 of the 20 experiments (65%) with VISSIM resulted in a bottleneck that met our criteria. Some of this discrepancy may be due to the criterion that failure in 50% of the model run replications would result in stating that a bottleneck is present. Under more stringent criterion been more stringent (e.g., 80%), the VISSIM predictions would be closer to FREEVAL.

Tables 5.6 and 5.7 summarize the frequency of bottleneck activations in the model replications of the study site, and the impacts of the bottleneck improvements. While all treatments resulted in some improvement on at least one identified recurring bottleneck site, the auxiliary lane constructed at NB I-270 segment 13 and downstream, generated the most improvement as it removed all bottleneck activations from two segments in VISSIM and 1 segment in FREEVAL. From a systems perspective, that treatment provided the most benefit, as it resulted in only 5 bottleneck activations in VISSIM and no activations in FREEVAL. Intuitively this is the treatment that would be expected to provide the greatest benefit as it would appear to add the most capacity. As shown in Table 5.7, the FREEVAL model never predicted more than one bottleneck at the test site. Because the congested conditions on NB I-270 segment 10 were determined not to be caused by a bottleneck on that segment, the tables show that a bottleneck was never activated in any of the replications.

Tables 5.6 and 5.7 also display the average freeway vehicle miles traveled (VMT) and average freeway mainline travel time. As expected, the improvements with the fewest bottleneck activations have the lowest corresponding travel times. It can be seen that even though the system ramp metering treatment showed the smallest reduction in bottleneck activations, in the VISSIM model, it produced the second largest reduction in average freeway through travel time and the second smallest standard deviation in average freeway through travel time. This demonstrates that while ramp metering may not remove an active bottleneck, it can significantly improve travel time and travel time reliability on the freeway mainline.

Table 5.6 I-270/I-44 Test Site: Bottleneck Activations and other MOE's--VISSIM Model

Baseline Recurring Bottleneck Location	Baseline Model	System Ramp Metering	NB I-270 Segment 13 Aux. Lane	NB I-270 Segment 13 Plus Lane	SB I-270 Segment 3 Off-Ramp Widening	SB I-270 Segment 5 Off-Ramp Widening
NB I-270 Seg 13	10/10	9/10*	0/10*	10/10*	10/10	10/10
NB I-270 Seg 10	0/10	0/10	0/10	0/10	0/10	0/10
SB I-270 Seg 3	5/10	5/10	6/10	5/10	0/10*	6/10*
EB I-44 Seg 5	7/10	4/10*	0/10	0/10	5/10	4/10
Total Bottleneck Activations	22	18	6	15	15	20
Freeway VMT Average (Std. Dev.)	197,028 (1,347)	182,494 (511)	186,343 (2,602)	176,483 (382)	182,827 (1,266)	181,289 (8,751)
Freeway TT** Average (Std Dev.)	5.685 (0.325)	5.713 (0.157)	5.442 (0.058)	5.682 (0.108)	05.620 (0.110)	05.615 (0.072)

** Bottleneck location directly targeted by treatment*
***TT: Travel time (min)*

Table 5.7 I-270/I44 Test Site: Bottleneck Activation and other MOE's--FREEVAL Model

Baseline Recurring Bottleneck Site	Baseline Model	System Ramp Metering	NB I-270 Segment 13 Aux. Lane	NB I-270 Segment 13 Plus Lane	SB I-270 Segment 3 Off-Ramp Widening	SB I-270 Segment 5 Off-Ramp Widening
NB I-270 Seg 13	Yes	Yes*	No*	No*	Yes	Yes
NB I-270 Seg 10	No	No	No	No	No	No
SB I-270 Seg 3	No	No	No	No	No*	No*
EB I-44 Seg 5	No	No*	No	No	No	No
Total Bottleneck Activations	1	1	0	0	1	1
Freeway VMT	190,545	190,545	190,982	190,982	190,545	190,545
Freeway TT*	5.770	5.770	5.548	5.548	5.770	5.770

** Bottleneck location directly targeted by treatment*
***TT: Travel time (min)*

5.2 Case Study 2: I-894, Milwaukee, Wisconsin

The study site is a 9.5 mile section of an urban freeway loop, I-894, in southwest Milwaukee, Wisconsin. The study section begins at the I-894/I-94 N-S interchange (Mitchell Interchange) and runs west and then north to the I-894 I/I-94 E-W interchange (Zoo Interchange). The available network and traffic data for this site are from 2003. It is worth noting as changes on the study site have been made since and a new nearby freeway interchange has been constructed and may affect traffic operations at the site.

Network geometry data were taken from aerial photography. PM peak traffic counts were provided by a consultant of WisDOT. These counts were first balanced against the two counting stations located within the study site, and the origin-demand matrix was developed using additional data from a previous study [66] and a proportionate distribution. The traffic demand information from the previous study was used to estimate the fluctuations in traffic demands across the study period.

The study section consists of 39 freeway segments as shown in Figure 5.11. It includes a major weaving segment (segments 18-19), a ramp weaving segment (segment 4), 11 on-ramp merge segments, 2 on-ramp lane add segments, 6 off-ramp diverge segments, and 3 off-ramp lane drop segments. The remaining 15 segments are basic freeway segments.

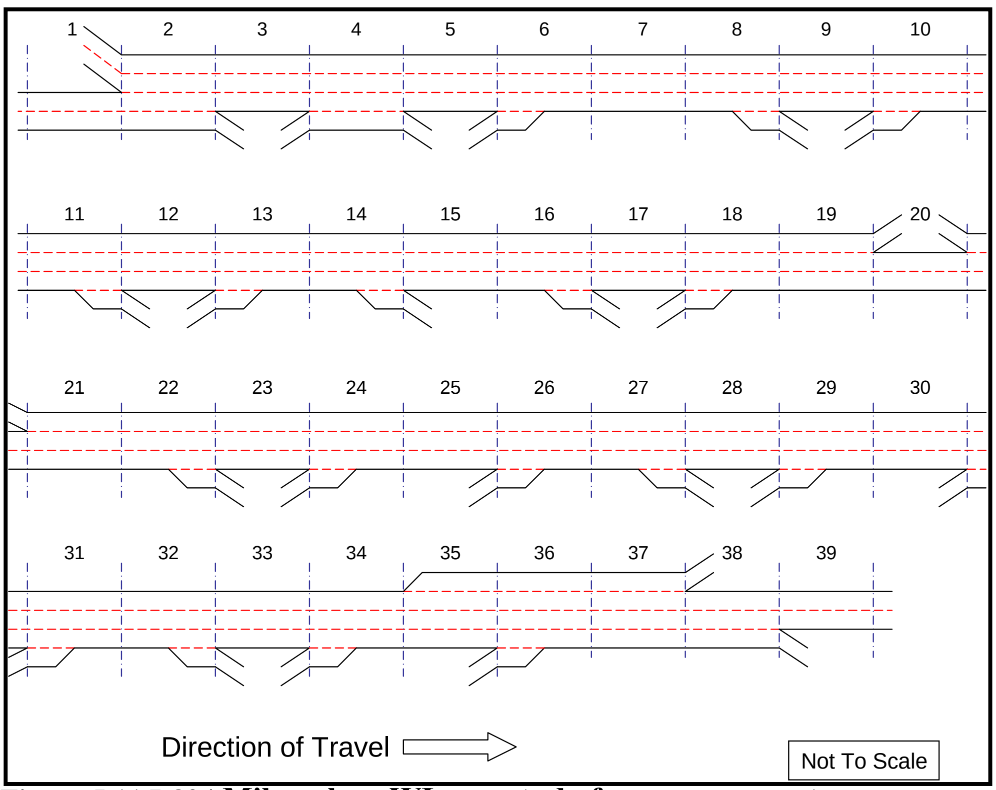


Figure 5.11 I-894 Milwaukee, WI case study freeway segments

The free flow speed (FFS) was taken as 60 mph based on the information from Hall et al [66]. The desired speed distribution in VISSIM was input as an empirical non-linear distribution from 52.8-74.6 mph. Ramp FFS speeds were estimated based on geometry and the ramp speeds at the I-270/I-44 study site, described previously.

Because of the lack of detailed speed and volume data at this site, calibration of the model was based on qualitative information gathered from contacts with staff of WisDOT [69]. The VISSIM model car-following and lane changing parameters were adjusted based on the results from the model application on the I-270/I-44 site (Case study 1), and the I-210 site (Case study 3). Calibration of the FREEVAL model consisted of adjusting segment type capacities to make them representative of the capacities calibrated in the VISSIM model. After the initial capacity adjustment factors (CAFs) were entered, some fine-tuning was necessary to generate queuing at the appropriate locations.

Baseline Conditions

Both FREEVAL and VISSIM models were run for three hours (twelve 15-minute periods). Time periods 4 through 7 represented the peak hour, with a calculated peak hour factor of 0.93. Using the aforementioned bottleneck criteria, the following bottleneck locations were identified in the models under baseline conditions:

Segment 4 (weaving section – 27th St. interchange): an active bottleneck was predicted in 7 of the 10 VISSIM replications, and in the FREEVAL model. The cause of the bottleneck is the short weaving section length of 320 ft.

Segment 10 (on-ramp merge – Loomis Rd. interchange): the existence of a bottleneck at this segment was predicted in all 10 of the VISSIM replications, and in FREEVAL. The cause of the bottleneck is a high mainline demand and a short taper type on-ramp (approximately 200 feet).

Segments 18-19 (weaving section – Hale interchange): This 3,000 ft section is a right-side on-ramp merge followed by a left-side off-ramp lane drop, as shown in Figure 5.12. The bottleneck is caused by a combination of high off-ramp demand (approximately 2,000 vph) and the weaving volume. Vehicles entering via the on-ramp and wish to exit via the left branch, are forced to merge three times including the initial merge from the ramp to the mainline. This bottleneck was active in 9 of 10 VISSIM replications and was also predicted in the FREEVAL model. Because the distance between ramps is 3,000 feet, it is divided into an on-ramp and off-ramp segment per HCM standards.

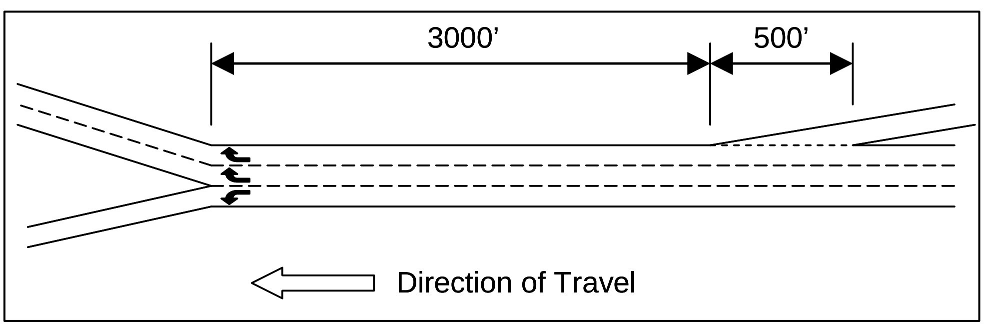


Figure 5.12 I-894 Segments 18-19 Weaving Section

Segment 31 (on-ramp merge – Lincoln Ave interchange): This bottleneck is created by the merging and mainline demand exceeding the available capacity. This bottleneck was predicted in 7 of 10 VISSIM replications. In the FREEVAL model, a maximum d/c ratio is predicted above 1, however, the maximum v/c ratio is predicted to be 0.981 and therefore no queue is predicted. The FREEVAL model does predict a decreased traffic speed (47 mph) and relatively high density (41 vpmpl) at the segment. Both models, do seem to represent the conditions of the segment as communicated by WisDOT staff [69].

Segment 34 (on-ramp merge – EB Greenfield Ave interchange): This bottleneck was predicted in 5 of 10 VISSIM replications. Similar to the upstream bottleneck at segment 31, the queuing is created by the demands of the mainline and on-ramp merge which are greater than the available capacity. In the

FREEVAL model, a maximum d/c ratio is predicted above 1, however, the maximum v/c ratio is predicted to be 0.994 and therefore no queue is predicted. The FREEVAL model does predict a decreased traffic speed (44 mph) and relatively high density (42 vpmpl) at the segment. Again, both models do seem to represent the conditions of the segment as expressed by WisDOT staff [69].

Bottleneck Mitigations

The following bottleneck improvements were modeled and evaluated for the bottlenecks identified at the study site:

- Auxiliary lane addition
- Off-ramp widening
- Fixed-time ramp metering

Segment 4 (weaving section – 27th St. interchange): The I-894 interchange with 27th St. is currently a short ramp weave (Figure 5.13). Two treatments were applied. The first, shown in Figure 5.14A, is conversion to a major weave with lane balance by extending the auxiliary lane through restriping past the off-ramp. This was modeled in both VISSIM and FREEVAL by adding a lane on the right to create four lanes in the basic segment immediately downstream of the weaving segment. In order to model the end of the auxiliary lane before the following on-ramp merge, an additional 3-lane segment was inserted. The second treatment is the one actually implemented by WisDOT at this location (Figure 5.14B). It involved physically removing the off-ramp of the weave, straightening the downstream on-ramp, lengthening the auxiliary lane through restriping, and signalization of the surface street intersection. WisDOT did place ramp meters on both of the on-ramps, however those were not modeled in this treatment.

These treatments removed the bottleneck activations in this segment as predicted by both the FREEVAL and VISSIM models. In FREEVAL, queuing was predicted immediately downstream at the second on-ramp of the interchange (segment 6). The capacity adjustment factors were not adjusted between treatments. VISSIM did not predict this occurrence. However VISSIM did predict changes in the bottleneck activations throughout the network, in addition to the one remedied at this location. The changes to the downstream bottlenecks can be mostly attributed to the change in the traffic pattern as well as the increase in arriving demand.

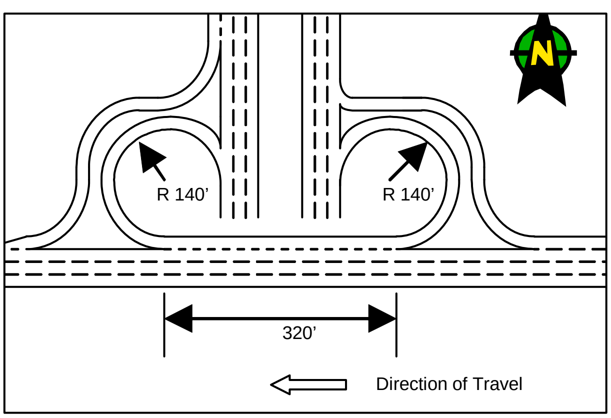


Figure 5.13 I-894 27th Street Interchange

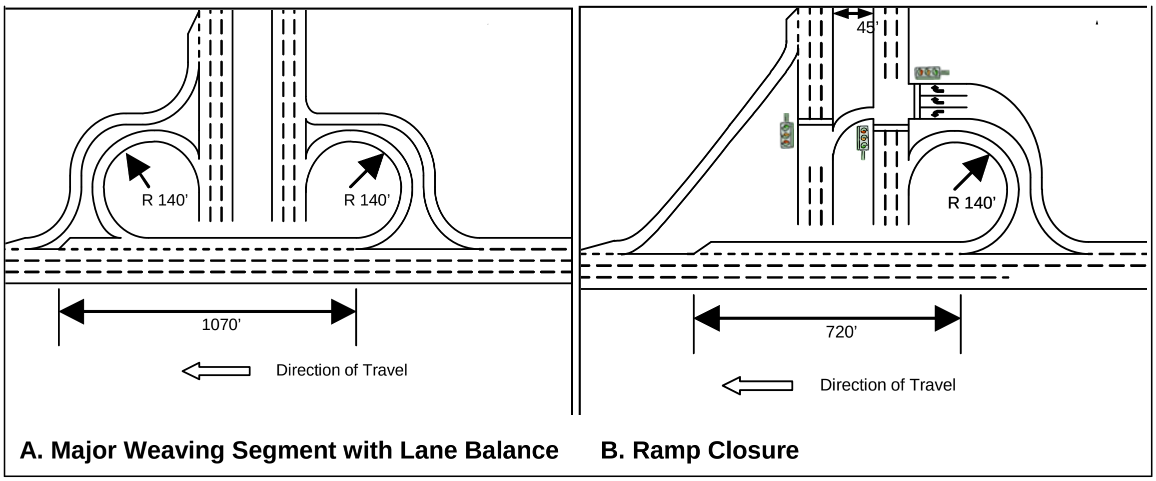


Figure 5.14 I-894 27th Street Interchange – Mitigations

Segment 10 (on-ramp merge – Loomis Rd. interchange): An auxiliary lane was added at this bottleneck location between the Loomis Rd. on-ramp to the downstream off-ramp at 60th St. The distance between the two ramps is approximately 2500' gore to gore, and would therefore create a ramp weaving section per HCM definition. This lane addition would be possible through restriping as both the left and right shoulder are approximately 11 feet wide. In VISSIM this treatment was modeled by adding a lane to the links between the merge and diverge links and connecting them appropriately. In FREEVAL, because the auxiliary lane created a ramp weave, the section was changed from an on-ramp merge segment and off-ramp diverge segment to a ramp weaving segment. This treatment removed the bottleneck activation in all VISSIM replications and in the FREEVAL model.

Segments 18-19 (non-HCM weaving section – Hale interchange): The treatment applied involves widening the exiting left-branch to two-lanes as shown in Figure 5.15A, which reduces the number of necessary merges and increases the capacity of the ramp. The proposed treatment resulted in only 2 of the 10 VISSIM replications showing a bottleneck, as opposed to 9 of 10 in the baseline conditions. However, this treatment would require widening the pavement, a bridge deck, and possibly require construction on a bridge overpass and would therefore be a relatively more costly and a long-term solution.

An alternative treatment was modeled that widened the ramp from the diverge gore to the viaducts, which is approximately 800' (Figure 5.15B). The intention was to remove queuing from the downstream end of the freeway and therefore at least provide improvement for the mainline through traffic. However, still it was not enough storage space for the queues, so the location still qualified as a recurring bottleneck.

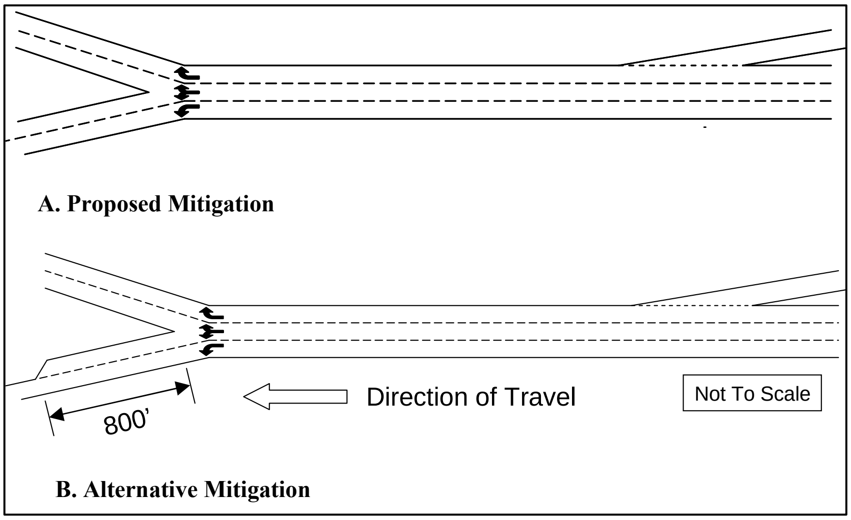


Figure 5.15 Hale Interchange Treatments

Segment 31 (on-ramp merge – Lincoln Ave): An auxiliary lane was added between the Lincoln Ave. on-ramp and the downstream off-ramp (Figure 5.16). The distance between the two ramps is approximately 3150'. This lane addition can be accomplished through restriping without narrowing the lanes. This treatment removed bottleneck activations at the Lincoln Ave merge in all of the VISSIM replications and the FREEVAL model. The bottleneck downstream at the EB Greenfield Ave. merge was activated 8 of 10 replications with this treatment as opposed to the 6 of 10 replications under the baseline conditions. This would be expected as traffic upstream of the EB Greenfield Ave. merge is able to flow more freely with less obstruction. The treatment also created an active bottleneck in the FREEVAL model at the EB Greenfield Ave. merge.

Segment 34 (on-ramp merge – EB Greenfield Ave): A schematic diagram of the baseline conditions of this merge area are shown in Figure 5.16. As can be seen in the figure, a left-side added lane already exists downstream of the ramp gore. This added lane becomes a freeway-to-freeway ramp in the Zoo interchange, hence the change in lane marking in the diagram. The treatment applied for this bottleneck was to simply extend the downstream lane-add to 1,000' upstream of the EB Greenfield Ave. on-ramp gore. This treatment could be applied via restriping. The applied measure resulted in no bottleneck activations in all 10 of the VISSIM replications and in the FREEVAL model.

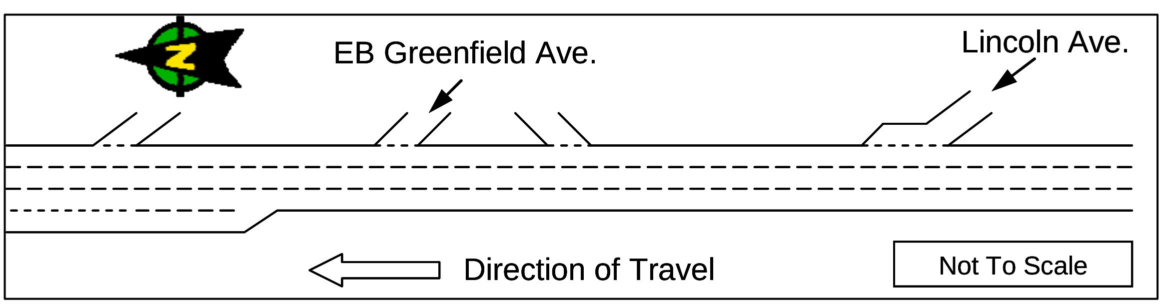


Figure 5.16 Lincoln Ave. and EB Greenfield Ave. merge areas

System-wide Treatments

None of the proposed treatments targeted at a specific bottleneck location resulted in significant improvements for the entire system beyond the targeted location, and may have resulted in bottleneck activations at other locations.. Two system-wide treatments were modeled:

Hale Interchange – Lincoln Ave. – Greenfield Ave*:* This treatment combines the individual treatments applied at the Hale Interchange, Lincoln Ave., and Greenfield Ave. bottleneck locations described previously. The treatment at the Hale Interchange is exactly as previously described and shown in Figure 5.14. The treatments of the Lincoln Ave merge and EB Greenfield Ave merge are slightly different than the first treatments described above. Figure 5.16 shows the baseline conditions set-up. The system treatments applied are shown in Figure 5.17.

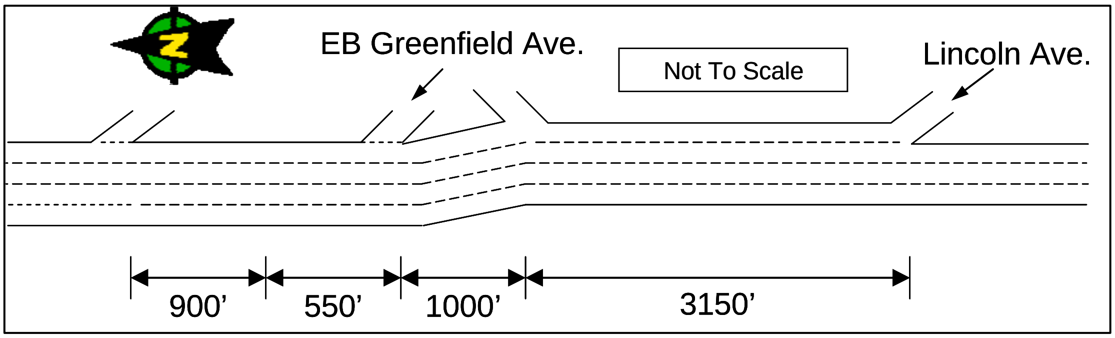


Figure 5.17 Lincoln Ave and EB Greenfield Merge Areas--System Treatments

The treatment involves changing the Lincoln Ave. on-ramp parallel acceleration lane to an added lane. Upon reaching the downstream off-ramp, instead of dropping the lane, as done when only treating the Lincoln Ave. merge, the lane continues and becomes the far right lane at the EB Greenfield Ave. on-ramp gore by way of lanes shifting. This can be accomplished through restriping because of the existing ample shoulder space and the fact that the ramps are taper type ramps. The benefit of this as opposed to simply combining the individual bottleneck treatments is a reduction in lane changing and a more even and stable flow.

Ramp Metering: Fixed-time ramp metering was implemented to all on-ramps with the exception of freeway-to-freeway ramps. The ramp metering rates were set similar to the I-270/I-44 case study. Ramp metering resulted in a minor reduction of the overall number of bottleneck activations. Only 2 of the original 5 predicted recurring bottlenecks in VISSIM were no longer categorized as recurring with the ramp metering in place. The weaving at segment 3 (27th St interchange) increased it's number of bottleneck qualifying replications from 7 to 9 out of 10. In the FREEVAL model bottlenecks were still predicted at the Hale Interchange and 27th St. weave with ramp metering in place. Queuing was not predicted at any of the other previously discussed locations.

Summary

Tables 5.8 and 5.9 summarize the results frequency of bottleneck activations in the model replications of the I-894 study site, and the impacts of the bottleneck improvements Table cells with an asterisk indicate bottleneck locations that are expected to directly benefit from the applied treatment.

Similar to the I-270/I-44 Missouri site, all modeled treatments resulted in an improvement on at least one identified recurring bottleneck location, as seen in Tables 5.8 and 5.9. The combined treatment of the

Hale interchange and Lincoln and Greenfield on-ramp merges, resulted in the best overall results in both the FREEVAL and VISSIM model based on bottleneck activations, average VMT, and average travel time. It is worth noting, that VISSIM eventually identified the Segment 13 on-ramp merge as a hidden bottleneck, and FREEVAL did not.

Similar to the I-270/I-44 site, the system ramp metering treatment showed the smallest reduction in bottleneck activations (Table 5.8) in the VISSIM model. Again, it resulted in the second largest reduction in freeway through travel time and the second smallest standard deviation in average freeway through travel time. This reiterates the statement that while ramp metering may not remove active bottlenecks, it can significantly improve travel time and travel time reliability.

TABLE 5.8 I-894 Test Site: Bottleneck Activations and other MOE's--VISSIM Model

Baseline Recurring Bottleneck Site	Baseline Model	27th St: Extend Accel. Lane	27th St: Ramp Closure	Loomis Rd: Aux. Lane (WA)	Hale Interch: Weave Reduction & Off-Ramp Widen	Lincoln Ave: Aux. Lane (WA)	Greenfield Ave: Lane Add	Hale/Lincoln/ Greenfield Treatments	System Ramp Metering
Seg 4--Weaving	7/10	0/10*	0/10*	7/10	7/10	7/10	7/10	7/10	9/10
Seg 10-- Merge	10/10	10/10	10/10	0/10*	10/10	10/10	10/10	10/10	10/10
Hale Int-- Weaving	9/10	9/10	8/10	10/10	2/10*	8/10	9/10	2/10*	8/10
Seg 31--Merge	7/10	6/10	6/10	6/10	9/10	0/10*	8/10	0/10*	4/10
Seg 34--Merge	5/10	8/10	8/10	6/10	6/10	8/10	0/10*	0/10*	4/10
Freeway VMT Average (Std. Dev.)	117,93 (433)	117,15 (334)	117,64 (424)	117,93 (430)	117,93 (435)	117,93 (433)	117,92 (433)	116,30 (432)	117,89 (475)
Freeway TT** Average (Std. Dev.)	11.24 (0.13)	11.12 (0.13)	11.25 0.20)	11.14 (0.17)	11.11 (0.15)	11.19 (0.16)	11.18 (0.14)	10.66 (0.08)	11.07 (0.13)

** Bottleneck location directly targeted by treatment*

***TT: Travel time (min)*

TABLE 5.9 I-894 Test Site: Bottleneck Activations and other MOE's --FREEVAL Model

Baseline Recurring Bottleneck Site	Baseline Model	27th St: Extend Accel. Lane	27th St: Ramp Closure	Loomis Rd: Aux. Lane (WA)	Hale Interch: Weave Reduction & Off-Ramp Widen	Lincoln Ave: Aux. Lane (WA)	Greenfield Ave: Lane Add	Hale/Lincoln/ Greenfield Treatments	System Ramp Metering
Seg 4--Weaving	Yes	No*	No*	Yes	Yes	Yes	Yes	Yes	Yes
Seg 10—Merge	Yes	Yes	Yes	No*	Yes	Yes	Yes	Yes	Yes
Hale Int--Weaving	Yes	Yes	Yes	Yes	No*	Yes	Yes	No*	Yes
Seg 31--Merge	No	No	No	No	Yes	No*	No	No	No
Seg 34-- Merge	No	No	No	No	Yes	No	No*	No	No
Freeway VMT	115,41	115,42	115,31	115,41	115,41	115,41	115,41	115,41	115,41
Freeway TT**	10.71	10.67	10.67	10.66	10.51	10.65	10.67	10.38	10.49

** Bottleneck location directly targeted by treatment*

***TT: Travel time (min)*

5.3 Case Study 3: I-210 Los Angeles, California

This is a heavily traveled 14 mile freeway section in the Los Angeles area, California (Figure 5.18) that experiences severe recurrent congestion in the morning peak period. The site and time period for the study was the west-bound direction of I-210 freeway from Vernon Street to Fair Oaks (on SR-134, just beyond the 210/134 junction), between 5:30 and 10:30 a.m. (Figure 5.18). The site has 21 on-ramps, four to five travel lanes on the freeway mainline and a median-side HOV lane that spanned the entire site and is separated from the mixed-traffic lanes by an intermittent barrier. In total, the site was divided into 65 sections. The study sections and the lengths and number of mixed-flow lanes in each section are shown in Figure 5.19.

Congestion typically starts around 6:00 a.m., peaks at 7:30 a.m., and finally dissipates at around 10:00 a.m. The cut-off occupancy for the HOV lane was two or more passengers per vehicle and was enforced at all times. All the on-ramps are metered and equipped with loop detectors (except the 605-NB/210-WB freeway connector). Each metered on-ramp had a corresponding main-line detector station for traffic-responsive control, and some, but not all, have HOV bypass lanes.

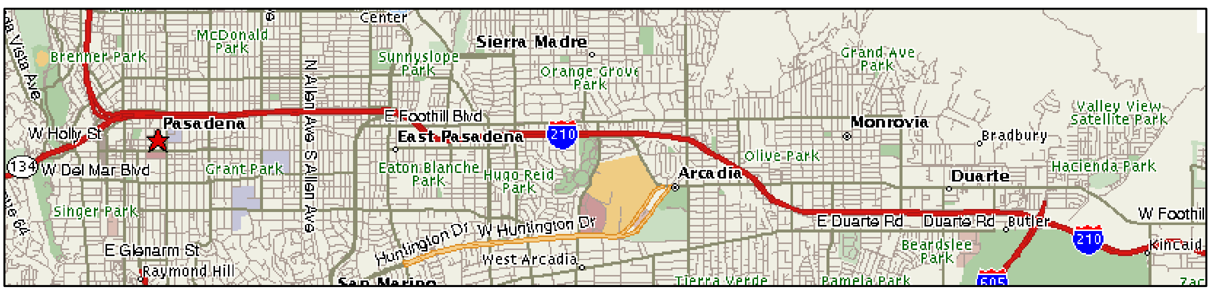


Figure 5.18 I-210 Test Site

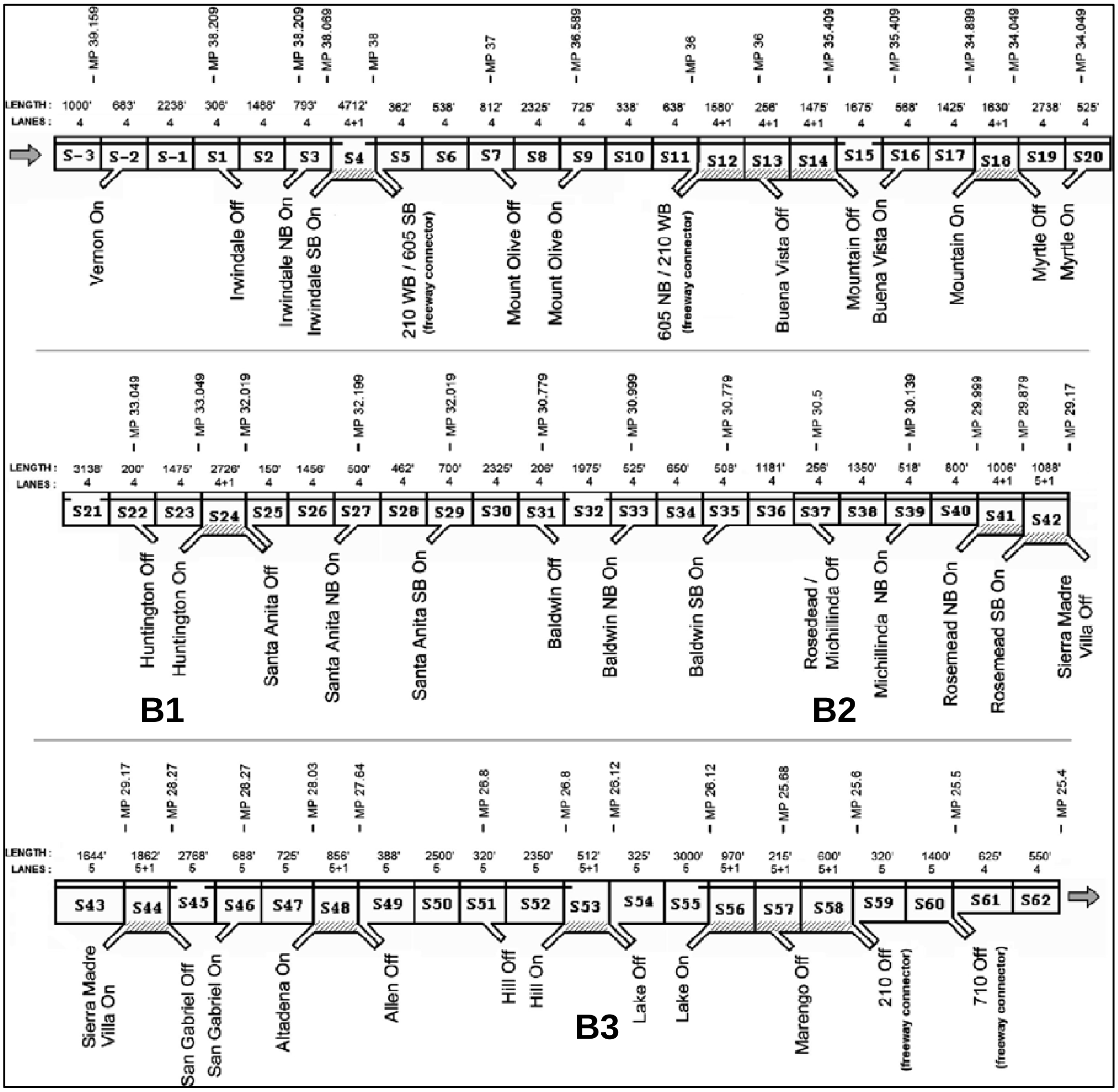
Identification of Recurring Bottlenecks

Loop detector stations in the study site are located approximately at 1/3 mile apart. They provide real-time data (counts, occupancies and speeds) at 30 sec intervals that are stored into the PeMS database. The loop detector data were analyzed to identify the location and causes of congestion on the I-210 study section. Figure 5.20 shows speed contour maps generated from the PeMS detector mainline data, that represent a heavy, a typical, and a light day of congestion on I-210. From these and other similar contour plots, three major bottlenecks were identified and described below:

Bottleneck B1 (Near Huntington Street, MP 33.049): This bottleneck was not easily explained with a simple comparison of nominal capacities and demands. The Myrtle ramps made no net contribution to the amount of traffic on the freeway. The Huntington on-ramps supplied about 500 vph to the main line, but this should easily have been absorbed by the auxiliary lane between Huntington and Santa Anita. The observed slow downs must therefore have been due to capacity reduction in the vicinity of Huntington and Santa Anita ramps. Localized capacity reductions are due to grades, curves, reduced visibility, street signs, and direct oncoming sunlight. In this case, the most probable cause is the series of reverse curves between Myrtle and Huntington ramps (as suggested by Caltrans staff).

Bottleneck B2 (near the Rosemead and Michillinda Street ramps (MP 30.139): This bottleneck is caused by the heavy traffic entering at the Rosemead and Michillinda on-ramps, which add approximately 1,700 vph to the freeway. These on-ramp flows should have been accommodated by the two additional auxiliary lanes. However, this increased capacity was apparently not fully utilized, probably because of increased weaving in that area.

Bottleneck B3 (Near Hill Street, MP 26.8): Mainline traffic near Hill Street (MP 26.8) was usually slow and sometimes fully congested. Traffic near Altadena (MP 28.03) almost always became completely congested. This bottleneck B3 is likely caused by a reduction in capacity due to the he S-shaped bend between Hill and Lake streets, and the heavy weaving taking place in the 800-ft auxiliary lane before the Lake off-ramp.



** the first three sections have negative indices because they were appended after the initial numbering*

FIGURE 5.19 I-210 Test Site sections and Bottleneck Locations

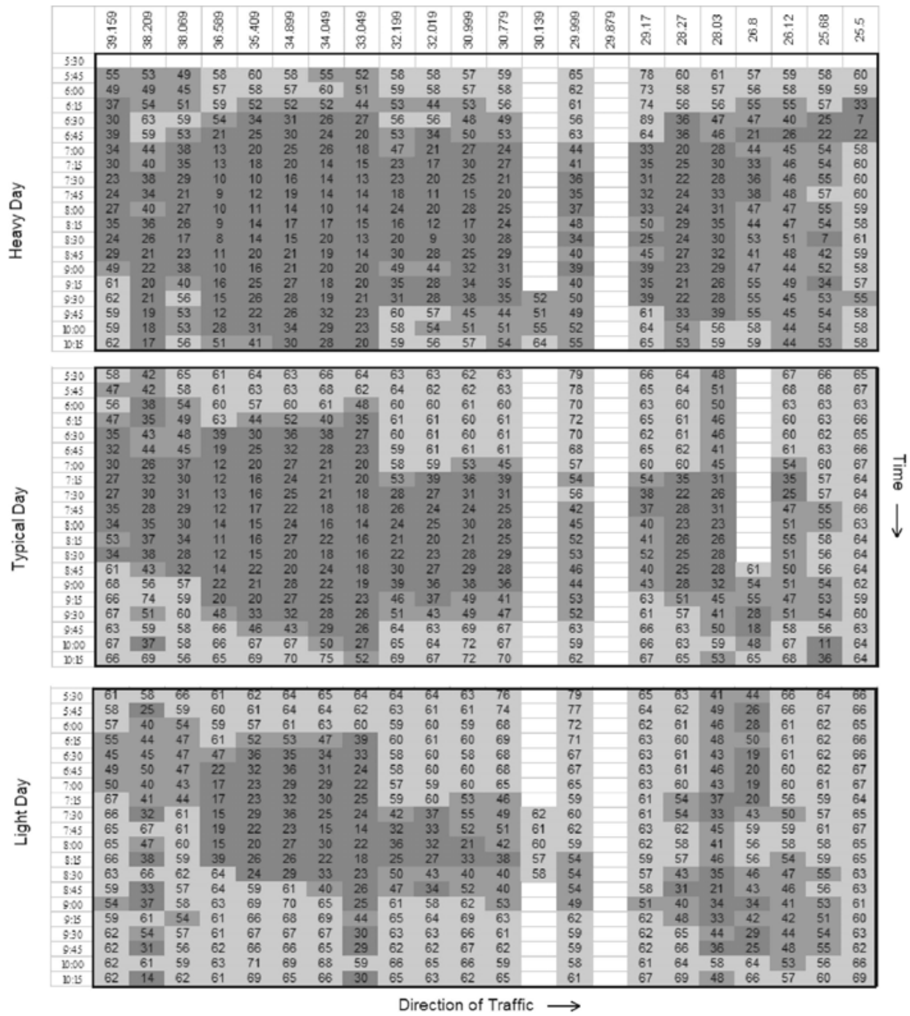


FIGURE 5.20 I-210 PeMS Speed Contour Plots

VISSIM Model Application

The study section has been coded and calibrated into the VISSIM and FREQ models as part of a research project to develop advanced ramp metering strategies [40, 70,71]. The time period of analysis was the am peak period (5:30 – 10:30 am).

The study site geometric characteristics were coded into VISSIM based on aerial photos and as built plans provided by Caltrans staff and aerial photos in bitmap format downloaded from MapQuest (www.mapquest.com). The HOV lane was modeled by creating a separate vehicle type for the HOV vehicles, and by closing the HOV-only lane to all non-HOV vehicles. Special link types (HardCurve, and SoftCurve) were introduced on selected links such as in the vicinity of the bottlenecks B1 and B3 to realistically model traffic operations at those locations. Also, a special procedure was used for coding the freeway connector from NB I-605 to avoid unrealistic ramp queues. A portion of the mainline vehicles was forced to evacuate the rightmost lane upstream of the ramp junction to accommodate the incoming flow from NB I-605.

The sources of traffic data were a) detector measurements stored in the PeMS database in 30 sec and 5 minute resolution, and b) manual counts on the ramps provided by Caltrans District 7 staff. Each ramp was surveyed over a period of about 14 consecutive days. However, there was no single day in which all ramps were surveyed simultaneously (a fairly common situation in real-world settings). Therefore, it was necessary to assemble a single composite day using ramp ounts from several different days considered as typical. The set of typical days was created by first discarding all Mondays, Fridays, weekends, and days with unusual events. From this set, a single day was selected for each on- and off-ramp.

Four vehicle types were defined in the VISSIM model: LOV, representing single occupant passenger cars, HOV, vehicles with two or more occupants that can use the HOV and bypass lanes, medium (HGV_MED) and large (HGV_LARGE) trucks. Two traffic compositions were defined: a) mixed-flow lanes (93% LOV, 3.5% HGV_MED, and 3.5% HGV_LARGE) and b) HOV lanes (100% HOV type).

The ramp counts were converted to origin-destination (O-D) matrices required by VISSIM using the O-D estimation routine of the FREQ macroscopic freeway corridor model [56]. FREQ produced a sequence of 20 O-D matrices—one for each 15-min time interval, separately for single occupant and HOV vehicles.

Model Calibration

The results from the initial simulation runs showed large discrepancies between observed and simulated congestion patterns, indicating the need for calibrating the model prior to analysis of improvements. The goal for the model calibration was to match key aspects of the freeway operation, i.e., the location of the three identified bottlenecks, spatial and temporal extend of congestion (queue lengths), utilization of the HOV lane, and on-ramp performance. Several model parameters had to be adjusted, as described below:

Look-back distance: Distance in anticipation of a bifurcation that the driver will begin maneuvering toward the desired lane (default = 200 m). This default distance appeared too small for large numbers of vehicles crossing over several lanes of traffic to reach their exits. But, increasing this value too much had the unrealistic effect of bunching up all of the exiting vehicles in the rightmost lane, far upstream of their intended off-ramp. These vehicles then obstructed other upstream off-ramps and on-ramps. It was therefore necessary to tune the look-back distances individually for each off-ramp in a way that allowed vehicles sufficient weaving space while ensuring that these lane-change regions did not overlap.

Waiting time before diffusion: A stopped vehicle will wait at most this length of time for a gap to appear in the adjacent lane; after the waiting time has elapsed, the vehicle is removed from the simulation (default = 60 s). This may result in unrealistic long queues and delays. This parameter was set to 1 sec., so vehicles stopped at the emergency stop position on the mainline (at the off-ramp bifurcation) were immediately removed from the simulation and thereby the obstruction to the freeway was minimized. Eliminating these vehicles had little impact on the freeway performance, because they were few and very close to their exit anyway. However, this may not apply to other bifurcations and lane drops within the network where larger waiting times are observed. To avoid such vehicles from being removed, a set of merge link types was created for on-ramp merge sections with waiting times of 60 sec (Table 5.10)

Car-following behavior parameters: the car-following mode of the freeway driver model in VISSIM involves ten tunable parameters: CC0 through CC9. Only the parameters CC0, CC1, CC4 and CC5 were changed in this study. Three separate sets of CC parameters were defined: Freeway, HardCurve, and SoftCurve. Each was paired with a merge link type, giving a total of six link types. The HardCurve and SoftCurve link types were applied only to the curved sections that affected bottlenecks B1 and B3.

CC0 and CC1 coefficients used in the calculation of the safe bumper-to-bumper distance, and affect the freeway capacity. Default values are CC0 = 1.5 m and CC1 = 0.90 sec. CC4 and CC5 influence the coupling between leader and follower accelerations. Lower values result in driver behavior that is more sensitive to speed changes of the preceding vehicle. Default values are CC4 = − 0.35 and CC5 = 0.35.

The parameter selection methodology consisted of multiple runs with different parameter values and comparison of simulated and observed speed and occupancy contour plots. The iterative procedure was stopped when all of the calibration goals were met. The final selection of driver behavior parameters is shown in Table 5.10. Figure 5.21 shows the model predicted speed contour plot with both default and calibrated parameter values. It can be seen that following calibration the model results are close to observed conditions (Figure 5.20).

Table 5.10 Calibrated VISSIM Model Parameters

Link Type	CC0 (m/ft)	CC1 (sec)	CC4	CC5	WTF (sec)
Freeway	1.7	0.9	-2.0	2.0	1
SoftCurve	1.7	1.1	-2.0	2.0	1
HandCurve	1.7	1.4	-2.0	2.0	1
Freeway Merge	1.7	0.9	-2.0	2.0	60
SiftCurve Merge	1.7	1.1	-2.0	2.0	60
HandCurve Merge	1.7	1.4	-2.0	2.0	60

time ↓

	39.159	38.209	38.069	36.589	35.409	34.899	34.049	33.049	32.199	32.019	30.999	30.779	30.139	29.999	29.879	29.17	28.27	28.03	26.8	26.12	25.68	25.5
5:30	63	34	24	62	61	63	62	63	63	63	62	64	62	63	63	63	62	63	64	63	30	61
5:45	12	6	7	62	58	63	62	63	63	63	62	63	63	64	64	63	62	64	64	62	8	61
6:00	6	5	6	62	59	63	62	63	63	63	62	63	60	62	62	62	59	62	51	6	5	61
6:15	5	6	8	62	46	61	62	62	62	63	59	61	59	63	63	62	60	63	5	4	4	62
6:30	7	7	8	63	41	61	60	61	60	62	52	58	51	54	59	47	14	4	3	4	4	63
6:45	7	7	9	61	41	59	60	59	57	59	45	40	24	21	11	3	4	3	3	3	4	63
7:00	6	7	8	61	51	62	62	62	29	23	3	2	2	3	2	2	3	3	3	4	5	62
7:15	5	5	6	62	53	60	61	9	2	2	4	3	3	3	2	3	4	3	3	4	5	63
7:30	5	7	8	61	50	45	5	2	2	2	3	2	3	3	3	3	4	3	4	5	6	61
7:45	7	6	8	61	14	2	2	2	2	2	3	3	3	4	3	4	5	5	6	6	5	62
8:00	7	7	8	43	2	2	2	2	3	3	4	4	4	5	4	4	4	3	3	5	6	61
8:15	7	7	8	3	3	2	3	3	3	3	3	3	3	4	3	3	5	5	5	5	5	61
8:30	4	3	3	3	3	2	2	2	3	3	4	4	4	4	4	4	5	4	5	6	6	61
8:45	3	3	3	2	3	2	3	3	3	3	3	4	4	5	4	5	5	4	4	5	5	63
9:00	3	3	3	3	3	2	2	3	3	3	4	3	4	5	4	4	5	4	5	5	6	62
9:15	4	3	3	2	3	3	3	2	3	3	4	4	4	5	4	4	5	4	4	5	5	63
9:30	3	3	4	3	3	2	2	3	3	3	4	3	4	5	4	4	5	5	5	6	6	61
9:45	3	3	3	2	3	3	3	3	3	4	5	4	5	5	4	4	5	5	4	5	6	61
10:00	3	3	3	3	3	3	3	3	4	4	4	4	4	4	4	4	5	4	5	6	6	56
10:15	3	3	3	3	3	3	3	3	3	4	4	5	5	5	4	4	6	5	6	7	7	61

Direction of traffic →

A. Default Model Parameters

	39.159	38.209	38.069	36.589	35.409	34.899	34.049	33.049	32.199	32.019	30.999	30.779	30.139	29.999	29.879	29.17	28.27	28.03	26.8	26.12	25.68	25.5
5:30	63	63	62	64	63	63	64	61	63	63	63	63	64	63	63	64	64	64	63	64	64	64
5:45	51	62	60	64	61	62	63	59	63	63	63	63	63	63	64	64	64	64	63	64	63	64
6:00	49	60	57	63	60	61	52	54	63	62	63	62	63	62	62	63	63	63	62	63	62	64
6:15	59	38	43	62	57	41	21	53	61	62	62	61	63	63	63	63	63	63	62	63	61	64
6:30	63	41	41	30	19	17	17	53	61	61	62	60	57	52	59	62	63	60	60	60	60	62
6:45	63	63	59	11	18	17	16	50	60	57	56	49	58	56	60	62	62	62	60	57	53	61
7:00	63	62	59	11	19	18	17	53	61	51	28	32	50	49	56	59	62	60	49	57	51	62
7:15	63	49	30	11	18	18	17	53	21	26	26	26	29	41	55	61	62	58	46	40	54	62
7:30	36	17	23	11	17	17	17	29	16	20	22	27	29	41	53	60	50	40	29	45	51	62
7:45	21	19	24	11	14	13	12	20	18	21	19	22	24	40	54	60	20	25	31	50	56	63
8:00	49	17	20	10	14	14	12	16	15	19	22	26	30	41	50	23	23	34	31	36	56	62
8:15	62	17	22	10	14	14	13	22	19	23	21	25	28	40	42	21	19	23	33	53	57	63
8:30	53	23	26	12	18	18	14	22	18	24	22	22	23	35	34	23	23	30	39	51	54	62
8:45	63	64	60	12	16	16	15	20	17	21	23	27	32	42	49	23	24	38	41	58	60	62
9:00	64	64	62	32	15	16	16	27	25	31	42	37	40	43	55	39	28	40	43	61	58	63
9:15	64	63	62	64	19	20	18	54	27	32	57	47	57	51	57	61	31	41	39	59	58	63
9:30	64	64	61	64	19	21	18	54	41	43	44	34	58	58	61	62	63	57	46	61	61	63
9:45	64	64	62	64	34	21	18	54	62	60	49	40	57	58	62	63	63	61	59	63	61	64
10:00	64	64	63	64	63	48	18	53	62	59	62	61	62	59	61	63	63	62	62	63	62	64
10:15	64	64	63	64	62	61	26	55	62	62	63	61	63	63	63	64	64	63	62	63	62	64

B. Calibrated Model Parameters

FIGURE 5.21 I-210 VISSIM Speed Contour Plots

On-ramp Metering Tests

System-wide ramp metering was tested with the VISSIM model at the I-210 site. The metering strategies tested are fixed-time control, ALINEA, and % Occupancy (% Occ). The performance measures used in the evaluation include travel times (veh-hrs) on the ramp, freeway mainline and total system, the average freeway mainline speed computed as the mean of the per link speeds over time and space, and the average throughput in vehicle-miles of travel (VMT) computed from the loop detector output. Simulations were performed in the am peak (5:30 am to 10:30 am). Ten model replications for each metering option were performed with different random number seeds.

Ramp metering was tested with and without queue override. The queue override prevents the on-ramp queue from spilling onto the surface streets. The controller enters the queue override mode whenever the queue detector placed near to the entrance to the ramp becomes “hot” while the speed on the mainline is above 35 mph. The queue detectors on I-210 are considered to be “hot" if they are continuously occupied for more than 3.2 seconds. In VISSIM a detector is “hot" when the smoothed occupancy rate is 40% or higher. However, if the average mainline speed is less than 35 mph, the on-ramp will remain in the normal mode, and the on-ramp queue will be allowed to invade the surface streets. This exception to the queue override is meant to avoid the on-ramp queue from being pushed into an already congested freeway. Once in the queue override the metering rate applied during the previous interval is increased by 120 vphpl, without exceeding the maximum metering rate of 900 vphpl.

Fixed-Time metering

Fixed-rate metering was tested with constant metering rates of 180, 300, 450, 600, and 900 vphpl, which correspond to integer-valued cycle durations of 20, 12, 8, 6, and 4 seconds respectively. A single metering rate was applied to all on-ramps. Performance measures for all of the tests are provided in Table 5.11. The values shown in the table are percent changes with respect to no on-ramp control. Thus, improvements over no control are indicated by negative values in the travel time columns and positive values in freeway mainline speed and VMT.

As expected, the freeway travel time was substantially reduced at low metering rates (450—180 vphpl) at a dramatic increase in on-ramp travel times that result in significant degradation of the whole system. The travel time measures (%TT) did not behave monotonically, but instead reached a minimum value in the 600 vphpl metering rate. In fact, 600 vphpl was the only level of metered on-ramp flow that performed favorably as compared to no control. The improvements in total travel time of 4.4% deteriorated quickly to an increase of 29.1% at the 450 vphpl metering rate because of the dramatic delay increases on the ramps. This suggests that selecting a single fixed metering rate for a large and complex site such as I-210 test section is a delicate task, and probably not a wise approach.

The % change in traffic performance for the different ramp metering rates was much smaller under queue override. The queue override ensures that huge delays on the on-ramp are avoided for low metering rates which also reduces the total system impacts (e.g., for 300 vphpl rate the total system travel time increases by 160% over no control with no queue override but only 1.5% with queue override). However, the maximum benefits are also reduced (the reduction of 4.3% became 1.5% at 600 vphpl)

Table 5.11 I-210 Fixed-Time Metering Results

Ramp Metering Strategy	Metering rate (veh/hr)	% CHANGE IN PERFORMANCE				
		On-Ramp TT	Fwy TT	Total TT	VMT	Fwy Speed
	180	2010	-35.4	358.5	-3.1	28.6
Fixed-time	300	967.2	-30.5	160.1	-0.5	24.4
	450	256.4	-23.6	29.1	0.3	18.4
No Queue	600	41.8	-14.2	-4.3	0.0	10.2
override	900	3.2	4.4	4.3	0.3	-2.2
	180	18.8	-2.9	0.9	0.1	2.1
Fixed-time	300	11.8	-0.8	1.5	0.1	0.4
	450	5.1	0.5	1.4	0.1	-0.3
Queue override	600	5.8	-2.6	-1.5	0.2	1.8
	900	-1.6	-3.4	-3.2	0.0	2.4

ALINEA control

ALINEA is a local traffic responsive ramp metering strategy. It determines the ramp metering rate based on real-time measurements of the detector occupancy at the merge area. The detector is placed downstream of the merge area, which is opposite to the conventional detector placement upstream of the on-ramp. Figure 5.22 illustrates the ALINEA control strategy [72].

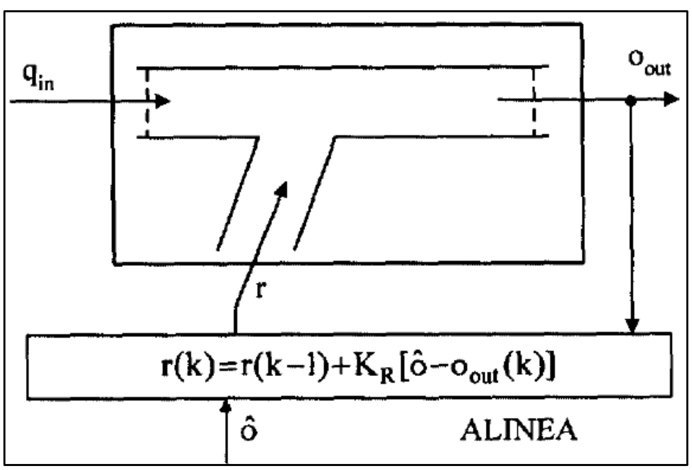


FIGURE 5.22 ALINEA Control Strategy

The two tunable parameters in the ALINEA control strategy are the target occupancy (^*o*) and a positive gain (K_R). The desired metering rate *r(k)* for the upcoming time interval *k* is computed as the measured flow entering the freeway during the previous interval *r(k-1),* adjusted by an amount proportional to the difference between the measured mainline occupancy o_{out} *(k)* and the target mainline occupancy. Thus, if the mainline occupancy is less than the desired value, ALINEA will increase the number of vehicles being released onto the freeway. The quickness with which the ALINEA control reacts is determined by the gain parameter K_R.

It has been suggested [72] that the target occupancy be set a little lower than the estimated *critical occupancy* at which the freeway transitions from the free-flow into congestion. Scatter plots from the VISSIM model suggest that its critical occupancy at this site is about 15% to 20%. The recommended value for the gain parameter K_R is 7,000.

Several simulation experiments were performed with the ALINEA strategy with and without queue override, to determine the best values of the parameters $\hat{o}$ and K_R, and investigate the strategy performance with upstream detector placement (which is common in US installations). First, the target occupancy $\hat{o}$ ranged from 8 to 40% for a constant gain value of K_R is 7,000. Next, different values of K_R (70, 700, 3000, 7000, and 20,000) were tested for two values of the target occupancy $\hat{o}$: 27.2% and 14.2%. Detailed model results are given elsewhere [40, 70]. Table 5.12 summarizes key findings.

For upstream detector placement, the value of 27:2% was the best choice for target occupancy. The value of $\hat{o}$ = 14:4% (i.e., free-flow conditions in the merge area) resulted in higher freeway mainline speeds at the expense of high delays on the on-ramp that diminish the system benefits. The performance with the downstream detectors is consistently better than with the upstream detectors for the low values of $\hat{o}$ = 14%, but upstream detectors perform better at high target occupancies (27.2%). The results from the model runs with queue override are similar to fixed-time metering; the freeway and system benefits are significantly lower than the no queue override. Similar results were obtained in all scenarios for values of gain K_R ranging from 3,000 to 7,000, with K_R = 20,000 being a near-optimal choice.

Table 5.12 I-210 ALINEA Metering Results*

Ramp Metering Strategy	Detector Placement	Target Occupancy (%)	% CHANGE IN PERFORMANCE On-Ramp TT	Fwy TT	Total TT	VMT	Fwy Speed
No Queue override	Upstream	14.4	163.8	-26.1	8.9	0.3	19.6
		27.2	60.3	-21.2	-6.7	0.3	14.5
No Queue override	Downstream	14.4	141.5	-26.6	4.2	0.1	19.9
		27.2	60.2	-20.1	-5.7	0.2	13.7
Queue override	Upstream	14.4	19.2	-7.4	-2.8	0.2	5.0
		27.2	10.6	-3.1	-0.7	0.2	2.0

** value of gain parameter K_R = 7,000*

Percent occupancy control

Under the %-Occ control, the metering rate is a decreasing linear function of the mainline detector occupancy, as shown in Figure 5.23. The two parameters in %-Occ control strategy are the low and high occupancy thresholds, o^l and o^h, at which the metering rate is assigned its maximum (900 vphpl) and its minimum rate (180 vphpl) respectively. There no generally published guidelines available for selecting the values of o^l and o^h. Typically, there are based on site specific calibrated values.

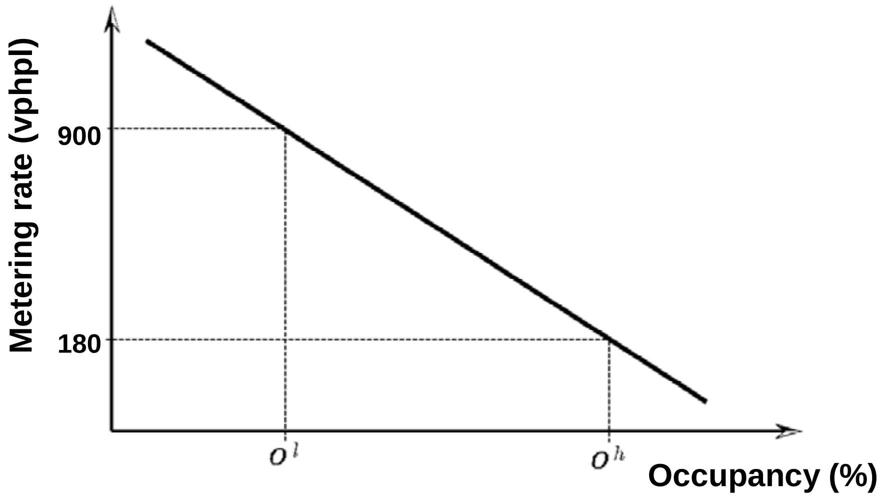


FIGURE 5.23 % Occupancy Ramp Control Strategy

A total of twenty six model runs were performed with parameter o^l ranging from 10% to 30%, and o^h from 18% to 30%. Sample results are shown in Figure 5.24. There is no recognizable trend and no obvious best choice. A maximum reduction of -7.4% in total travel time was obtained with parameter values o^l = 14% and o^h = 30%. As with ALINEA and fixed-time metering , enforcing the queue overrides reduces the travel time reductions. In general, no general recommendation for tuning the %-Occ controller parameters can be extracted from the results. It is concluded therefore that some savings can be expected with %-Occ, but that optimizing its performance for a given freeway may be difficult.

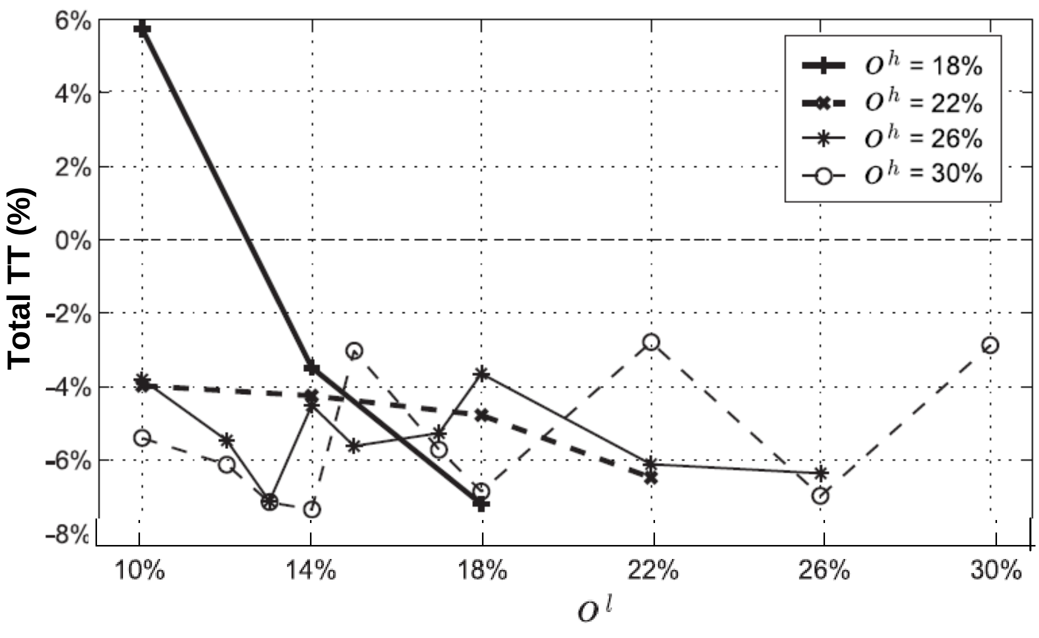


FIGURE 5.24 % Occupancy Ramp Control Results

5.4 Case Study 4:   Attica Tollway, Athens, Greece

Attica tollway is a 40.5 mile (65.2) long urban freeway in Athens, Greece. The tollway started being delivered in segments in May 2001 and it was completed in late spring 2004, prior to the 2004 summer Olympics in Athens. The 15.4 km (9.6 mile) spur of Attica Tollway (Figure 5.25) leading to the center of Athens through mountainous terrain (segments B, K, M, P, X, Y) has 56 tunnels and cut-and-cover sections which comprise 12% of its length. Drivers enter the freeway through 39 toll plazas located at the entrances to the freeway and at each on-ramp. Drivers pay a toll only once on entry (open tolling system) and the toll is the same at all entry points.

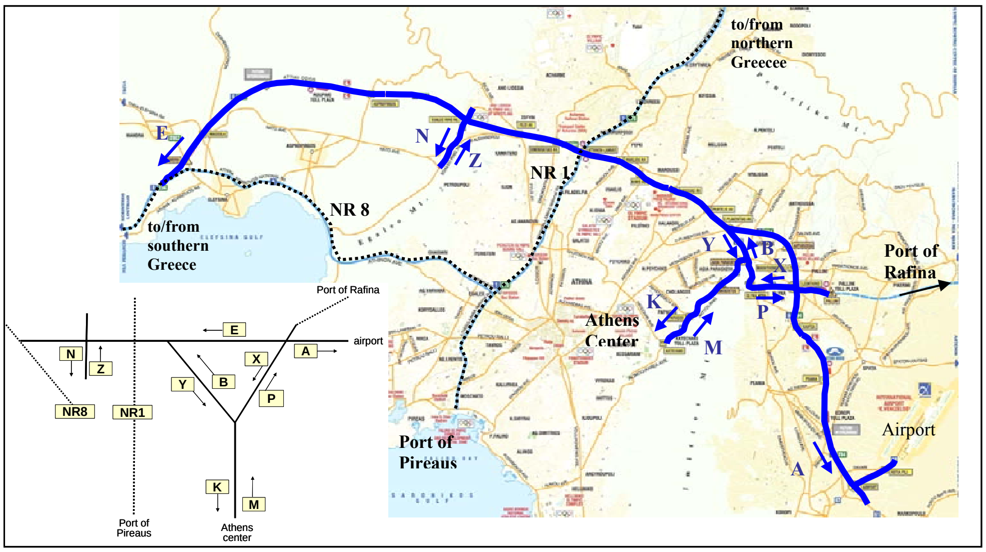


Figure 5.25 Attica Tollway Segments

In 2009, the average number of weekday vehicle entries through the toll plazas was about 339,000 compared with 332,000 in 2008 and 323,000 in 2007. The daily tollway volumes correspond to approximately 6-10% of the total traffic in the Athens metropolitan area.

Attica Tollway has a comprehensive ITS infrastructure for traffic surveillance and incident management consisting of: 220 Closed Circuit Television (CCTV) cameras placed every 1000 m in open sections and every 125 m in tunnels and covered sections, 11 meteorological stations; 600 inductive loop sensors every 500 m (0.3 m) in open sections and every 60m in tunnels; 600 Emergency Roadside Telephones (ERT) every 2000m in open sections and every 60m in tunnels (on both sides); 103 Variable Message Signs (VMS) located on the mainline upstream of key decision points and on each access road to the Tollway (AVMS); Lane Control Signs (LCS) and Variable Message Signs (VSLS) every 150m in tunnels and on key gantries in open sections. The loop based vehicle detection stations provide real-time data on traffic volumes, speeds and occupancies per lane at 20 sec intervals. The data are stored and processed at the Attica Tollway Traffic Management Center (TMC).

Bottleneck Identification

Traffic is free-flowing in most segments of the Attica tollway. The main problem area was the complex, congested freeway to freeway merge of segments M and B onto the main line E on the Attica Tollway, where the situation was exacerbated by the presence of a busy on-ramp from the toll plaza also merging in the vicinity of the freeway-to-freeway merge (Figure 5.26).   In addition, E and B freeways merge into a four-lane cut-and cover tunnel shown as the shaded block in Figure 5.26. Furthermore, approximately

900 ft (300 m.) downstream the right-of-way (ROW) is permanently limited to a width of 48 ft (14 m.) by the Suburban Railway tracks on the left and a massive retaining wall on the right.

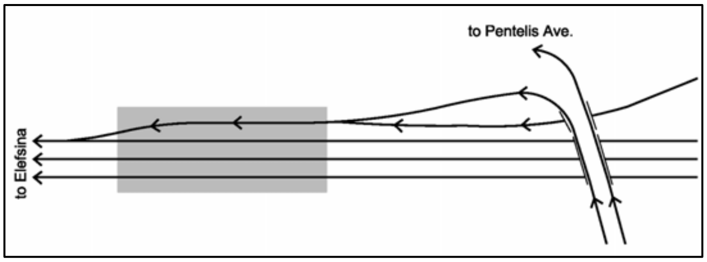


Figure 5.26 Study Bottleneck – Attica Tollway--Existing Conditions

Speed profiles from loop detector data confirmed the presence of bottleneck at this location. Also, queues were formed 90% of the time and lasted on average two hours reaching up to 3 km (1.8 mi). In addition to the field data, numerous motorist complaints regarding excessive delays were received. The major steps of the investigation for bottleneck resolution are presented below. Detailed description is given elsewhere [73].

Model Application

Several analysis tools were tested to assess the bottleneck impacts and proposed improvements. However, initial application of macroscopic models such as FREEVAL and FREQ12 showed that they are not capable to address the complex geometry of the merging freeways and the vehicle interactions. Thus the assessment of existing conditions and the evaluation of the alternatives were based on the predictions of the VISSIM microscopic model. It should be noted that the agency staff also applied the INTEGRATION model which produced similar results to VISSIM.

Geometric input data for the study area were obtained from detailed construction plans. Traffic volumes were obtained from the loop detector data stored in the TMC. An important element of the input data was the definition of the peak hour period, given that this freeway facility is less than two years old and its traffic patterns are relatively unknown. Fridays carry about 20% more traffic in the peak period than the rest of the weekdays. Given the relatively high growth experienced on Attica Tollway, the Friday traffic volumes were used as more representative of longer-term traffic loads on the facility.

The model calibration consisted of comparing field data on average speed and queue lengths with simulation outputs. The basic calibration adjustment was changing VISSIM's CC2 "headway" parameter from the default of 0.9 to 0.8. The model produced very close speed and delay estimates and to the field conditions.

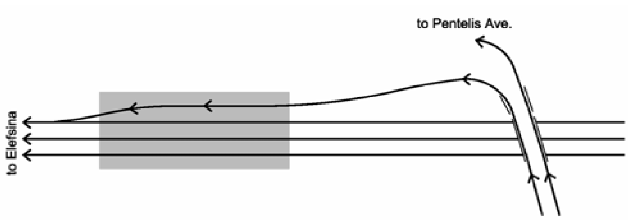
Bottleneck Improvements

The development of alternative scenarios for improving the subject bottleneck was mostly based on the experience of the transport engineers of the Tollway operating and maintenance company (Attikes Diadromes SA). This process also identified a number of feasibility or cost-prohibitive constraints, such as the replacement of viaducts and the demolition of large retaining walls. Another important constraint was that traffic conditions should remain largely uninterrupted during construction, if possible, because these freeway sections carry heavy traffic volumes.

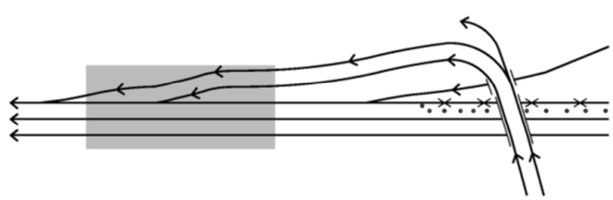
A number of promising alternative scenarios were examined as shown in Figure 5.27, including 1) ramp metering with existing geometry, 2) on-ramp closure from segment B, 3) widening to provide two narrow merging lanes from segment B, and closure of upstream mainline lane to provide an open lane for the on-ramp, 4) same as scenario (3) with closed on-ramp, and 5) re-alignment of the on-ramp to merge on segment E instead of segment B.

Promising scenarios were also analyzed with traffic volumes augmented by 20% to account not only for latent demand but also to assess whether i) the bottleneck resolution will have a reasonably lasting impact since it is expected to take at least a few years for such growth to materialize, and ii) to test whether this bottleneck resolution along with latent demand and growth may lead to other bottleneck(s) downstream.

1. Existing Geometry -- Ramp Metering

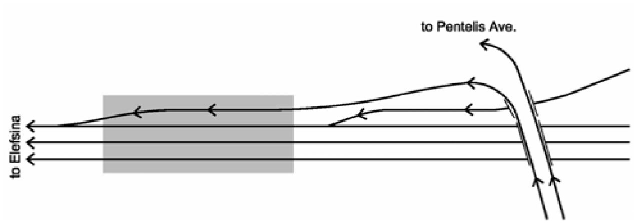


2. Traffic Lane Arrangement with Closed On-Ramp



3. Two Lane Ramp from B to E --Closed Upstream Mainline Lane

4. Same As Scenario (3) With Closed On-Ramp



5. Re-alignment – On ramp Merge on E instead of B

Figure 5.27 Scenarios for Bottleneck Improvements

The results from the simulation of ramp-metering (scenario 1) showed that the queues were worse than the base case. Also, ramp metering is non-existent in Greece, so its implementation at a single location during the three hour am peak period would be risky, cumbersome and potentially ineffective. A conventional traffic signal was also tested, which is odd at a freeway-and-ramp merge. However, local drivers are familiar with such signals and compliance was not expected to be a problem. It did provide unacceptable performance due to long queues.

Scenario 2, closing the toll-plaza on-ramp provided only a modest relief but the deleted access to more than 1,000 vehicles during a three hour peak period window, assuming that there would be a temporary and not permanent closure of this centrally located access point, was an unacceptable consequence.

The traffic re-alignment with closure of the right mainline lane on freeway E added unnecessary complexity. It was expected to require manual deployment of traffic cones in addition to lane closure illuminated signs to effectuate the lane closure due to imperfect compliance by motorists, exacerbated by the "sheep effect" of other motorists following the violator. This, however, is an option that may be exercised in the future due to the relatively high significance of the B freeway and the presence of a downstream 3-lane tunnel section.

The re-direction of the on-ramp from merging onto segment B on to merging onto segment E (scenario 5) provided the best results in traffic performance according to the VISSIM model (the predicted delays were practically zero), and its implementation was feasible.

Field Implementation and Evaluation

The simulation results were convincing enough for the concession companies of Attica Tollway which decided to implement the proposed bottleneck improvement. The actual cost of the project in first quarter of 2006 figures was 700,000€ (or U.S. $875,000), with design costs comprising about 6% of the total. The entire bottleneck improvement project which included a fair amount of construction was executed in about 16 months from problem definition and analysis, to design, financing, and implementation.

A large number of "before" and "after" field data were collected in order to evaluate this bottleneck mitigation project. Flow, occupancy and speed data were obtained from the loop detectors. Queue lengths were obtained from the camera recordings. Sample travel times were also collected with probe vehicles. The results indicate that the average speeds improved substantially, and queues largely disappeared. Also, no secondary downstream bottlenecks appeared. The profile of speed over space (Figure 5.28) illustrates the propagation of congestion with significant speed reduction upstream the bottleneck ("before" conditions) and the absence of any congestion propagation "after" the bottleneck resolution.

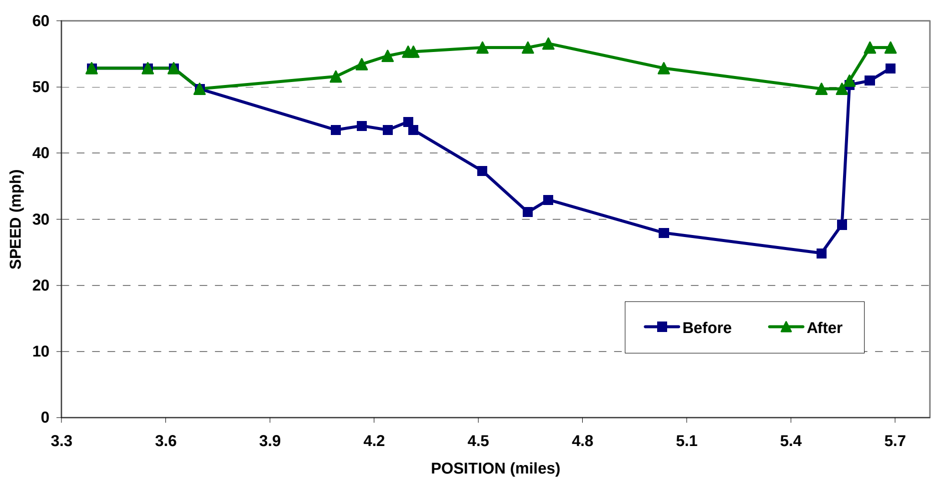
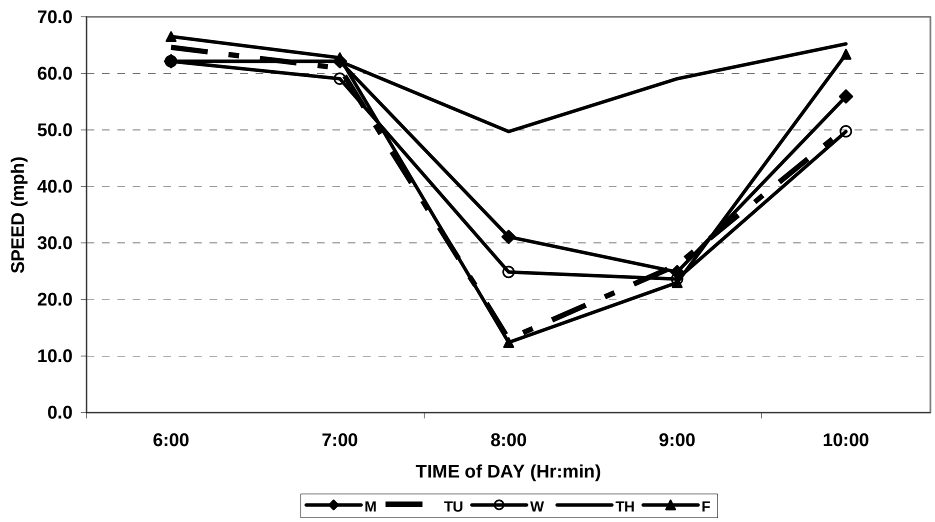


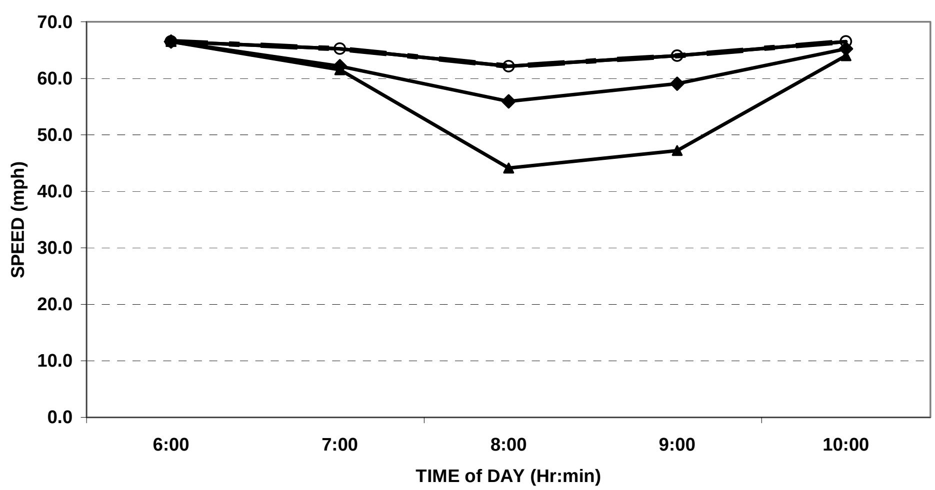
Figure 5.28 Sample Speed Profile--Weekday Morning Peak Period

Significant improvements were realized in the frequency and extent of queues on the freeway. In the "after" period, queues were formed only in 12% of the weekdays as opposed to 90% of the weekdays in the "before" period. The maximum queue length for the days with queues present was 0.6 mi (1 km) compared to 1.9 mi (3 km) in the "before" conditions. The average queue duration was 120 min "before", and 57 minutes "after".

The average speeds per day of the week for the am peak upstream of the bottleneck on Freeway B are shown in Figure 5.29. Following the bottleneck removal, the average speeds are close to free-flow speeds or about 100 km/hr (~60 mph.) every day (Figure 5.29B) except on Friday which is the most heavily traveled day of the week, with 20% more traffic volumes than the average weekday.



A. "Before"



B. "After"

Figure 5.29 Average Speeds—Weekday Morning Peak Period

CHAPTER 6
CONCLUSIONS

6.1 Bottleneck Identification and Classification

A bottleneck is defined as a roadway section where the traffic demand exceeds the normal freeway capacity, resulting in formation of queues upstream of that location and free-flowing traffic downstream. The bottleneck is called “active” when traffic flow through the bottleneck is not affected by downstream restrictions (spillback from downstream bottlenecks). Recurrent bottlenecks occur on the same location and time periods of the day. Their behavior and characteristics are reproducible over many days. A “hidden” bottleneck typically occurs when traffic demand is metered by an upstream bottleneck. It becomes active only when improvements to the upstream bottleneck are made, and the full traffic demand manifests itself at the hidden bottleneck location.

Average speed is used by most operating agencies to the bottleneck location(s) and the spatial and temporal extent of the congestion. Speeds upstream of the bottleneck are typically less than 30 mph. Speeds at the bottleneck location range between 40 to 60 mph depending of the measurement location (vehicles accelerate as they travel through the bottleneck), and traffic free-flowing downstream with speeds at or above 60 mph. Density contour plots also can be constructed from aerial photographs of the study section taken at successive time intervals. The bottleneck is located in the freeway section with high density values upstream, and associated low flows and speeds, while downstream of the bottleneck high speeds and low densities are observed. The start and length of the activation period (duration of congestion) may vary over days because of the variability in traffic demands.

Another approach is the use of cumulative vehicle count vs. time (“N curves”) to identify and characterize freeway bottlenecks. N curves of flow vs. time are constructed at each detector station. The original N curves are shifted horizontally by the average free-flow trip time from their respective locations to the most downstream detector location. Any vertical differences between the curves indicate excess vehicle accumulations due to the presence of an active bottleneck.

Surveillance systems (loop detectors, radar, video) are increasingly used for freeway monitoring and control. They provide real-time vehicle count, speed and occupancy (density) data per freeway lane at 20 or 30 second intervals. Time-series or contour plots of real-time occupancy or speed data at successive loop detector pairs can pinpoint the bottleneck location. Typical detector occupancy values are generally above 30 percent upstream, and less than 10 percent downstream of the bottleneck location. Past studies and extensive analyses of detector data show a minimum activation time of continuous 30 minutes.

An algorithm was developed and implemented to identify bottlenecks from surveillance data. The algorithm looks into the measurements detector from successive detectors and declares the existence of a bottleneck if the following conditions are satisfied for a minimum of continuous 30 minutes:

- There is an increase in speed of at least 20 mph between the current detector and the one immediately downstream.
- The speed at the current detector is less than 40 mph.
- The detectors are less than 3 miles apart.

Similar criteria were used in identifying bottlenecks based on the outputs from the selected analysis tools.

Recurrent freeway bottlenecks occur wherever there is either a surge in demand or a restriction in the available capacity. The two most frequently reported causes of recurrent freeway bottlenecks in the agencies' interviews were capacity restrictions and weaving sections. While most interviewees also mentioned that demand surges at on-ramps are a significant cause of bottlenecks, agencies from large metropolitan areas are concerned with demand exceeding capacity in the entire system.

The recurrent freeway bottlenecks were classified into three types by considering the demand and capacity characteristics of the facility in question:

- Type I bottleneck: demand surge, no capacity reduction (freeway on-ramp merge locations, system-wide excess demand)
- Type II bottleneck: capacity reduction, no demand surge (lane drop, long upgrade, horizontal curve, narrow lanes, lateral obstructions such bridges and tunnels)
- Type III bottleneck: combined demand surge and capacity reduction (weaving sections, diverge bottlenecks, interchanges)

Figure 6.1 summarizes the classification scheme

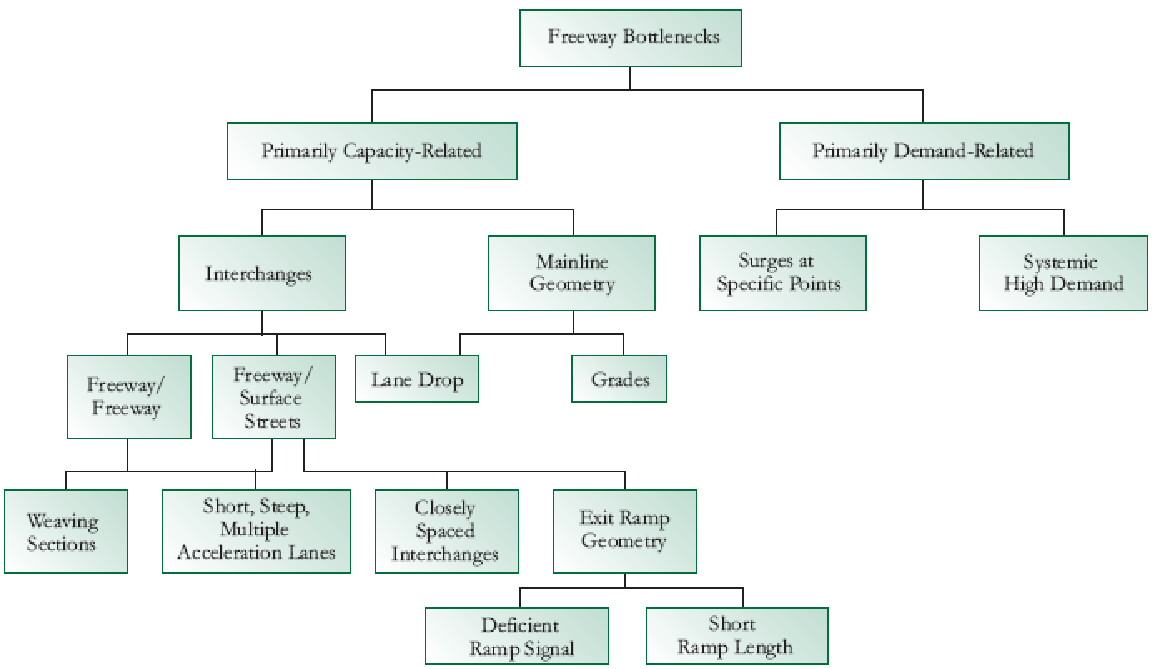


Figure 6.1 Bottleneck Classification

6.2 Low Cost Bottleneck Improvements

A number of geometric and operational improvements for recurring bottlenecks have been proposed and implemented. Table 6.1 (adapted from Table 4.1) shows a matrix of bottleneck causes to bottleneck improvements. In the interviews conducted with the operating agencies the most frequently mentioned low-cost bottleneck improvements were: ramp metering, auxiliary lanes, and HOV lanes. While lane width reductions/restriping were also mentioned by three respondents, two agencies mentioned that many of these opportunity locations have already been converted, and there is now a hesitancy to reduce lane widths due to safety concerns.

Interview results suggested that there are differences in approach to low-cost bottleneck improvements between the U.S. and European agencies. European agencies appear to favor "dynamic" bottleneck improvements, which tend to utilize ITS concepts to re-route traffic using traveler information, or employ "dynamic" lanes, while US agencies tend to use more "static" improvements, such as the construction of auxiliary or HOV lanes. Ramp metering is an exception which seems to be popular both in the U.S. and Europe.

Table 6.1 Bottleneck Improvements

Table 3. Mapping Bottleneck Problems to Mitigation Measures

Bottleneck Types	Mitigation Measures											
	Auxiliary Lanes	Collector-Distributor Road	Paved Right Shoulder	Paved Left Shoulder	Shoulder/ Plus Lane	Re-Stripping to Add More Narrow Lanes	All Purpose Lane (Concurrent or Reversible)	HOV Lanes (Concurrent or Reversible)	Truck Reversible	Ramp Metering	Temporary Ramp Closures	Traffic Diversion Information
Heavy On-Ramp Demand	++	-	+	-	++	+	++	-	+	++	-	+
Weaving Sections	+	+	+	+	+	++	++	++	+	-	-	+
Lane Drops	++	-	++	-	++	++	++	++	+	+	+	+
Tunnels and Bridges	-	-	-	-	-	++	-	+	++	-	-	+
Horizontal and Vertical Curves	++	-	++	++	++	-	++	+	++	+	+	+
Narrow Lanes and Lateral Obstruction	+	+	+	+	+	-	+	+	++	+	+	+
Inadequate Accelerated and/or Decelerated Lanes	++	++	++	-	++	+	+	+	++	+	++	++

++ = good solution, + may be helpful, - = not helpful

In the four case studies, the following bottleneck improvements were successfully tested:

- Ramp metering
- Off-ramp widening
- Auxiliary lane construction
- Restriping and lane-narrowing in conjunction with plus-lane
- Restriping without narrowing lanes
- On-ramp re-alignment

The modeled improvements resulted in the removal of existing bottlenecks in each test section with the exception of I-210 (case study 3). The ramp metering strategies tested resulted in freeway performance improvements but could not completely remove the bottlenecks because of the high traffic demands and constraints (queue storage plus uncontrolled freeway connector.

6.3 Assessment of Analysis Tools

Both microscopic stochastic models (CORSIM and VISSIM) and a macroscopic deterministic tool (FREEVAL) based on the HCM methodology were applied in four case studies to model freeway facility operations and analyze potential low cost bottleneck mitigation measures. Comparison of model predictions against field data when available, indicate that both modeling approaches can reasonably replicate field conditions.

It is important that the analysis tools are properly calibrated prior to the analysis of mitigation measures. However, model calibration is a complex process and depends on the availability and accuracy of field data. It is essential that a calibration strategy be established that involves the number of parameters to be calibrated, performance measures and targets for the study section. At a minimum the analysis tools should be able to identify correctly existing bottleneck and their impacts (queue formation and dissipation) in time and space.

The number of minimum inputs required for a modeled freeway facility varies greatly depending on the scope of the network and what traffic operation features are to be included. In general, FREEVAL requires relatively minimal data compared to the microscopic VISSIM model, and may take approximately 10 minutes to enter depending on the size of the modeled facility. A model can be created with as little information as mainline and ramp volumes, free-flow speeds, segment type, number of lanes and capacity. However, FREEVAL is not suited for situations of networks with interacting bottlenecks, complex geometries and dynamic traffic control as illustrated in Case studies 3 and 4.

FREEVAL is a macroscopic model and its computer run time is negligible. The computer run times for the VISSIM microscopic model depend greatly on the size, complexity, and number of vehicles modeled in the network. Also, multiple model replications are required because of the stochastic nature of the VISSIM model. This can make the entire VISSIM modeling process very time consuming. Modeling of I-270/I-44 (case study 1) required approximately 70 minutes per replication, while modeling of I-894 (case study 2) required 40 minutes.

While both the tested models can predict the impacts of existing recurrent bottlenecks and analyze bottleneck treatments, FREEVAL's ease of use, and its ability to show active and hidden bottlenecks, demonstrates that it is better suited for modeling existing conditions and common operational improvements (e.g., auxiliary lanes) on the freeway mainline. The model complexity and flexibility of VISSIM make it a better tool for modeling operating conditions on complex freeway networks and interchanges and determining their effects on the entire network including surface streets.

It may be useful to consider a hybrid approach where FREEVAL is initially employed for active and hidden bottleneck identification, followed by the use of VISSIM runs to characterize system performance under baseline and treatment conditions. The VISSIM runs would also be used to identify freeway bottlenecks created by off-ramp spillback since FREEVAL does not have this facility at this time.

Tables 6.2 and 6.3 summarize and compare key characteristics of VISSIM and FREEVAL models. Table 6.2 displays each tool's modeling capabilities and limitations, and Table 6.3 shows the user investments needed to apply the models.

Table 6.2: VISSIM and FREEVAL Model Capabilities Summary

CATEGORY		VISSIM	FREEVAL
Bottleneck Identification Capability	Active Bottlenecks	From processed output only	d/c > 1.0; upstream queue present
	Hidden Bottlenecks	Requires multiple runs to reveal hidden bottleneck after active one(s) is treated	d/c > 1.0; no upstream queues; active upstream bottleneck
	Speed profiles	From processed output only	In standard output
	Drop in mainline throughput upon queue formation	Can be modeled	Cannot be modeled*
Types of Recurring Bottlenecks that can be modeled	Heavy on-ramp demand	Can be modeled	Can be modeled
	Weaving Sections	Can be modeled	Can be modeled
	Heavy off-ramp demand causing spillback on mainline	Can be modeled	Cannot be modeled
	Lane drops	Can be modeled	Can be modeled
	Tunnels and bridges	Coded as speed reduction zone and/or user-defined link type, resulting in reduced capacity	Coded as reduced capacity segment via capacity adjustment factor (CAF)
	Horizontal and vertical Curves	Grades can be input. Coded as speed reduction zone and/or user-defined link type.	Grade effect on capacity can be modeled
	Narrow lanes/ lateral obstruction	Coded as speed reduction zones and/or user-defined link type	Reduced free-flow speed (FFS), and capacity using HCM
	Short accel/decel lanes	Can be modeled	Affects density in ramp influence areas
Modeling Low Cost Treatments	Auxiliary lanes	Can be modeled	Can be modeled by changing segment type to a weaving section
	Peak-hour or plus lanes	Modeled using time-dependent signal, parking spaces, or transit stops	Can be modeled
	Paved shoulders	Can be modeled	Can be modeled as reduced capacity lanes using CAF
	Re-striping ; add narrow lanes	Modeled as reduced speed zones	Modeled as reduced capacity lanes or reducing the free flow speed of the facility.
	HOV lanes	Can be modeled	Cannot be modeled**
	Truck restrictions	Can be modeled	Cannot be modeled
	Ramp metering	Can be modeled	Can be modeled fixed time only
	Temporary ramp closures	Can be modeled- traffic manually reassigned	Can be modeled by converting ramp segments to basic segments. - traffic manually reassigned.
	Traffic diversion information	Cannot be modeled—manual diversion only	Cannot be modeled—manual diversion only
	Exit ramp widening	Can be modeled	Can be modeled, but has no impact

**Capability being added as part of SHRP II L08 Project*
***Capability being added as part of NCHRP 3-96 Project*

Table 6.3: VISSIM and FREEVAL Model User Investments Summary

CATEGORY		VISSIM	FREEVAL
Required Model Inputs	Time-Varying Traffic Demands	Mainline, on- ramp demands; O&D volumes	Mainline and on-ramp demands
	Link geometry attributes	Flexible and user defined	HCM segment types only
	Variable Link FFS	Coded as speed zone if variable	HCM FFS speed estimation equation
	Vehicle types	Multiple user-defined	Cars, Trucks, RV's
	Ramp geometry	Detailed	Ramp FFS and # of lanes
	Single/Multiple Facilities	Allows single or multiple	Directional Facilities only
	Single/Multiple time intervals	Allows both	Allows Both
Input and Output Data Processing and Model Calibration	Ease of input coding	Simple, but time consuming – WI case study input required 8-10 hours	Very quick input process; WI case study input required 10-15 minutes
	Model calibration scope	Multiple calibration parameters	Handful of calibration parameters
	Bottleneck identification process in the model	Requires detailed output processing of link by link speed	Requires no additional processing of output
	Number of runs required	Minimum of 10 replications are needed	Macroscopic- single replication
	Quality of output related to fidelity of treatment impact	High fidelity with calibrated model	Medium fidelity with calibrated model
	Model running time (Dell MS Windows XP Intel 3.20GHz)	0.7 hours per replication for WI site, total 6.7 hours	1-2 minutes per run- no replications

VISSIM

The input coding of a VISSIM model is not particularly difficult, but it takes considerably longer than that for FREEVAL. For example, the I-894 Milwaukee, WI site, a unidirectional 10 mile facility, took approximately 8-10 hours to model with VISSIM, compared to only approximately 15 minutes to create the same model in FREEVAL. This time does not include the time required for model replication and calibration.

Because VISSIM has many default input values, a user would minimally need to enter the roadway geometry using appropriate link types, vehicle network inputs and paths (origin-demand matrices), traffic control devices, and signal timing plans. Information regarding link types, vehicle classes and types, traffic types, desired speed distributions, lane-changing behavior and car-following behavior parameters have pre-set defaults, but can be adjusted by the user for greater accuracy and control. Features used in this study that are not necessarily required inputs include reduced speed zones and speed decisions. All of the features and inputs mentioned in the preceding text each have multiple of available inputs and parameters that can be adjusted so that the user can create as accurate of a model as desired.

Bottleneck identification from VISSIM output is more complicated than in FREEVAL. The VISSIM output provides a large number of performance measures in text files that need to be processed to obtain the link performance measures (e.g., speeds and densities) required for bottleneck analysis. This may take upwards of 4 hours to extract the desired information. However, the process is automated through user created data reduction and processing software and a set of 10 model runs can be completed in as little as 20 minutes. It is recommended that a summary output feature be added to the VISSIM software package that is particularly geared toward bottleneck identification. This feature would significantly reduce the overall model application process. Also, currently it is not possible to determine the presence of a hidden bottleneck from the VISSIM output. This can only be determined by simulating the treatment at the active bottleneck and determine whether a new bottleneck appears downstream of the treated location in a second set of runs.

VISSIM can explicitly model most freeway configurations and bottleneck geometric treatments tested in the case studies directly or through adjustment of the model parameters and features. Examples include modeling of narrow lanes and off-ramp widening. Traffic slowdown because of lane narrowing is modeled by creating reduced speed zones. A slow down in VISSIM will generally result in a reduction in link capacity because of the car-following logic. To maintain the same link capacity, or a user specified capacity value it would require creating a special link type and adjusting the driver parameters. In the case of off-ramp design modifications, it is necessary to consider the route lane change distance of the link connectors, because this distance determines when the vehicles will begin to attempt a lane change. This could be set to a distance used throughout the model or the location of a sign for example.

VISSIM cannot directly model temporary lane closures or openings (e.g., hard shoulder use during peak periods, incidents). The modeling approach used in this study was to place signals on the freeway lane that had a green signal indication only during certain times in the simulation (when the travel lane was open to traffic). Other suggested approaches included i) placing a parking space in the lane that the user desires to be closed, and forcing a vehicle to park in that space at a specified time span, ii) placing a transit stop at the location of the closure and setting the dwell time equal to the length of the desired closure.

Both fixed-time and traffic responsive metering strategies were tested with VISSIM model. In the I-270/I-44 and I-894 and Attica Tollway case studies simple fixed time ramp metering was applies at selected on-ramps. In the I-210 case study traffic responsive strategies with and without queue override were implemented through customized code using the software's C based scripting feature. VISSIM was found to be a suitable tool for modeling complex control strategies on typical freeway systems

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FREEVAL

FREEVAL appears to be well suited for many types of bottleneck analyses since (a) it is HCM based and therefore fits into the existing planning analysis processes, (b) most of the input data required for this model are routinely available from state DOTs and MPOs, and c) it is system-based and therefore can deal with the issue of hidden bottlenecks. An attractive feature in FREEVAL is the ability to calibrate capacities with field observations, using a capacity adjustment factor (CAF). This is especially useful in modeling certain mitigation measures, such as the use of a shoulder, or narrower lanes may not add a full-lane capacity to the bottleneck section. By properly calibrating these capacities using field data the true impact of the mitigation measure can be assessed.

FREEVAL's ability to output segment demand and volume along with multiple performance measures allows for easy identification of active and hidden bottlenecks. The outputs of the FREEVAL model are reported in tables and graphs that are fairly intuitive. No manipulation or processing of the data and information is necessary to put it in an easy to read format. The replicating of the model itself typically takes less than a minute, and since only one replication is needed, the time required to model, replicate, and analyze a unidirectional freeway facility is approximately 20 minutes.

Modeling narrower lanes through restriping is carried out through by entering the new lane and clearance widths. FREEVAL uses HCM methodologies to adjust the free-flow speed curve and segment capacity. Capacity can also be altered using the capacity adjustment factor, as stated above. Further auxiliary lanes can be added during specific time intervals (e.g. the plus lane). Treatments that incorporated the addition of, change of type in, or removal of a weaving section did not seem to require any additional changes other than adjusting the number of lanes in the appropriate segments and changing the segment type. In some instances, the addition or subtraction of a segment may be necessary. Again user desired capacity values can be obtained through the use of capacity adjustment factors as appropriate.

FREEVAL limitations stem from its underlying principles of HCM methodology. It cannot explicitly model multiple interacting bottlenecks, and interchange configurations with complex geometrics (Case study 4). FREEVAL does not place a capacity constraint on off-ramps, therefore high off-ramp demands or downstream capacity constraints (such as the presence of a signal) do not propagate congestion on the freeway mainline. This also means that off-ramp widening or other improvements at the downstream end of an off-ramp cannot be modeled.

FREEVAL can only model fixed-time ramp metering per time period. FREEVAL uses a simple input-output approach to calculate the queue lengths at on-tramps. Queues on an on-ramp that may spillback onto surface streets are not accounted for. Furthermore, the reported benefit of avoiding the “capacity drop” due to ramp metering is not currently modeled. FREEVAL does not recognize the difference between uninterrupted and queue discharge capacities. While this does not affect queue formation, it does affect the discharge of queues and therefore affects the duration of the queue and the activation and duration of downstream queues.

6.4 Recommendations for Further Research

This following sections present recommendations for additional research efforts to improve the methodologies, tools and processes in the analysis of recurrent freeway bottlenecks.

Interface of Real-Time Data with Modeling Tools

Modeling tools require both input data for the model application (e.g., traffic demands) and performance data for the model calibration prior to the analysis of alternative improvements (e.g., speed or density contours). This process can be greatly facilitated if procedures would be developed to automatically obtain the required data by the models from real-time data. Examples include:

- Automated conversion of real-time detector counts to traffic demands. This process should include procedures for balancing flow data from successive loop detectors for input to modeling tools. Also, in many surveillance systems, off-ramp counts are not available, and there is a need for procedures to estimate the missing values from mainline and on-ramp detector data.
- Recommended default values and adjustment factors for capacity based on the analysis of field data. For example, what is the “capacity drop” during flow breakdown, and what is the added capacity due to low-cost improvements such as full shoulder use on the right or left side of the travel lanes? Accurate estimates of these factors greatly improve the accuracy of the analysis of existing and projected bottlenecks.

Enhancements of Algorithms for Bottleneck Analysis Using Real-Time Data

In this work, an algorithm for bottleneck identification was successfully implemented inside the PeMS real-time archival data system. The algorithm automatically processes the detector data, identifies bottlenecks and produces performance measures including bottleneck duration, queue length and delay. It is proposed to extend this approach in two different ways:

First, extent this algorithm to work on other real-time archival systems. The parameters that we have used, and the implementation steps that we have selected in this study are specific to the PeMS system.

Second, the application of the bottleneck identification algorithm in real-time. The real-time aspect has several issues that need to be investigated. Examples include:

- The current algorithm has a lag of at least five 5-minute periods, or 25 minutes. It's unclear if this lag is too large for the algorithm to be useful in the real-time context.
- The time to process the data in order to identify bottlenecks might be an issue. Not only there is a need to look at the most recent data samples in order to check the thresholds, but also a need to look at the historical data in order assess whether each bottleneck has been persistent for a sufficient length of time. When doing this at the end of the day it's easy to pull all of the necessary data out of the database and perform the computation once. But when running this computation every 5 minutes this might be an issue.
- It might be possible to leverage historically identified bottlenecks with real-time bottleneck estimation. This would give users a sense as to whether the recurrent bottlenecks are simply recurring or whether the currently identified bottleneck has never been seen (in which case this reduces to an incident detection algorithm).

Enhancements to the FREEVAL Model

Despite the rather simplistic nature of the recurring bottleneck definition, accurate quantitative modeling of low-cost bottleneck treatments is the ultimate goal. This work has shown that bottleneck identification appears not to be problematic in a simulation environment. However, future research should focus on calibrating the effects of the improvements (e.g., narrow lanes, plus lanes, shoulder use, etc) on observed capacity, and verify the modeled treatment performance with comparable field observations.

Possible enhancements to the FREEVAL modeling tool involves adding features to i) improve the practical application by end users, ii) better model the impacts of existing and projected bottlenecks and iii) evaluate explicitly certain operational improvements that it currently cannot explicitly model.

- Automated conversion of freeway facility geometry from sections (mainline distances between ramps) to HCM-based segments (basic, on-ramps, off-ramps and weaving).
- Automated sensitivity analysis to variations in demand and capacity to allow the assessment of the effect of daily fluctuations in traffic, and enable the identification of true, recurring bottlenecks in which d/c remains above 1.0 even with small fluctuations in demand or capacity
- Developing bottleneck-specific output, including location, activation time, length of activation, and queues and delays associated with each bottleneck.
- Implementing adjustments to the HCM capacity values to simulate queue discharge rates during breakdown ("capacity drop").
- Improving the modeling of interacting bottlenecks.
- Modeling bottlenecks that are activated by off-ramp spillback onto the freeway mainline (e.g. due to downstream signal).
- Automated identification of queue spillback onto the adjacent surface street, particularly when implementing ramp metering
- Implementing lane by lane analysis for truck restrictions / HOV lanes

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Appendix A.

Interview Guide

NCHRP 3-83 STUDY "Low-Cost Improvements for Recurring Freeway Bottlenecks"

A freeway bottleneck is the critical point of freeway congestion with queues upstream and freely flowing traffic downstream. Recurring bottlenecks (those not caused by atypical conditions such as incidents) can occur for many reasons, including high volumes of merging traffic, lane drops between ramps or at off ramps, weaving sections, horizontal or vertical curves, and long upgrades.

The objective of the NCHRP 3-83 research project is to develop a technical guide for identifying existing and future recurring freeway bottlenecks and determining appropriate low-cost geometric and operational improvements to mitigate their effects on traffic flow.

Task 2 of the research project is concerned with gathering experiences from State DOTs and other operating agencies on their approaches for identifying recurrent freeway bottlenecks and determining low-cost improvements. This document serves as a guide for interviews of selected jurisdictions.

INTERVIEW GUIDE

General Background Information

- Who are you?
- What jurisdiction are you reporting for?
- What others share roles in addressing freeway bottlenecks?
- How many lane-miles of freeway your jurisdiction cover?
- What is the annual VMT on the covered freeways?
- Roughly how many major freeway bottlenecks have you identified in your system?

Main Bottleneck Causes

- What are the main causes of freeway bottlenecks in your area?
    - Capacity restrictions (lane drops, grade increases, narrow lanes, curves, tunnels, bridges, etc.)
    - Demand surges (on-ramps)
    - Weaving sections
    - Other (explain)
- Have any bottleneck or congestion studies been done? (Are copies available?)

Practices for Bottleneck Analyses

- Does your jurisdiction have an operational definition of a recurrent freeway bottleneck? (If yes, what is it?)
- Do you generally analyze bottlenecks at the freeway facility level or at the individual bottleneck location level?
- Which performance measures does your jurisdiction use to analyze bottlenecks? Do you use any of the following measures:

- Average Speed
- Throughput (discharge volume)
- Queue length (miles)
- Delay (veh-hrs)
- Extent of the congestion (hrs)
- Other

- What type of data collection system is used to analyze recurrent freeway bottlenecks?

Electronic Surveillance

- Loop detectors;
- Other detectors (e.g., radar, ultrasonic, infrared);
- Cameras; and
- Probe vehicles

- What is the number of sensors used to collect data? (i.e, detector spacing?)
- What is the frequency of data collection?

Other Means

- Floating cars (with and without GPS)
- Manual traffic counts

- Are the bottleneck analyses performed in real-time or off-line?
- Which analytical techniques do you use to analyze bottlenecks?
    - Sketch Planning Tools (Queuing Diagrams)
    - Highway Capacity Manual
    - Simulation Models
    - Other
- What are some of the advantages & limitations of the analysis techniques you currently use?

Bottleneck Improvements

The research study focuses on low-cost geometric and operational improvements for recurrent freeway bottlenecks (e.g., auxiliary, shoulder, narrow, high-occupancy vehicle, reversible, and contra-flow lane designs; ramp metering; truck restrictions). The study is not concerned with major construction projects such as freeway widening that address bottlenecks but these types of projects are expensive and take several years to plan, design, and construct.

- Types of bottleneck improvements analyzed and/or implemented by your jurisdiction
- Do you have any recent recurrent congestion freeway bottleneck improvement studies your jurisdiction has performed? Can you send these to us?
- Have you done any evaluation of the performance of the bottleneck improvements your jurisdiction has undertaken?

- What are the costs of bottleneck improvements your jurisdiction has undertaken? (What qualifies as a low-cost improvement in your jurisdiction?)
- What are the benefits of bottleneck improvements your jurisdiction has undertaken over their operational lifetimes?

Operational Policies and Practices

- What are the recurrent freeway bottleneck goals and objectives set by the jurisdiction?
- How do the results of the recurrent freeway bottleneck analysis affect the planning and financial programming of freeway improvement projects?
- In your opinion, what are the strengths and weaknesses of how your jurisdiction identifies and mitigates bottleneck locations?
- Who are the stakeholders/other jurisdictions involved in the analysis, management and mitigations of freeway bottlenecks in your area?
- What institutional issues/arrangements impede/promote successful projects in your jurisdiction?
- Are there any other comments helpful to understanding how your jurisdiction addresses recurrent bottlenecks?

Jurisdiction Characteristics

- What is the annual budget of your jurisdiction?
    - Is the overall budget split into planning, operations and construction accounts?
    - How low-cost bottleneck improvements are funded?
- How many full-time equivalent (FTE) employees does your jurisdiction have?
- What are the annual budget and staff positions (FTE) for freeway operations?
- What are the jurisdiction policies or legislative mandates regarding freeway bottlenecks?