NCHRP 3-83

Low-Cost Improvements for Recurring Freeway Bottlenecks

Draft Technical Guide

November 2012

TRANSPORTATION RESEARCH BOARD
NAS - NRC
LIMITED USE DOCUMENT

Kittelson Associates
in Association with:
Dr. Nagui Rouphail, ITRE, NC State University
Dr. Karl Petty, Berkeley Transportation Systems
Mr. Brian Eads, Crawford, Murphy & Tilly
Mr. Joseph McDermott, McDermott & Associates

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CHAPTER 1
INTRODUCTION

Problem Statement

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.

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.

The impacts of bottlenecks can often be mitigated through relatively low-cost geometric and operational improvements (e.g., auxiliary lanes, ramp metering, truck restrictions). 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.

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 of freeway, further complicating the cause and effect interrelationships of each. Bottleneck analysis is a complex undertaking and involves data processing, algorithms for analysis of real-time data, and modeling tools that consider both local and system-wide impacts.

Overview of the Technical Guide

The guide provides application procedures for bottleneck identification and classification, analysis of the local and system-wide bottleneck impacts, and determination and assessment of mitigation measures. It is based on the research described in the NCHRP 3-83 final report. The material is organized into three Chapters:

Bottleneck Analysis: Definition of recurrent freeway bottlenecks, bottleneck identification algorithms. Bottleneck causes and classification scheme. Bottleneck analysis tools: capabilities, features and application requirements.

Low Cost improvements: A taxonomy of low-costs bottleneck improvements. Mapping of bottleneck causes to mitigation measures. Benefits and costs of bottleneck initiatives. Funding approaches for bottleneck improvements

Procedures for Application: Guidance on performing a freeway analysis study; definition of the study area, data requirements and sources, and application of real-time algorithms and modeling tools to identify and classify bottlenecks, and assess the select mitigation measures.

CHAPTER 2
BOTTLENECK ANALYSIS

2.1 Definition of Bottlenecks

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. Thus, it is important to always consider the system-wide effect of bottleneck improvements, some of which may actually have adverse consequences on the system performance. Bottlenecks may offer the opportunity for mainline metering to effectively manage the location and system-wide impacts of congested flow.

There is also a reduction in discharge flow following the bottleneck activation. 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. 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.

2.2 Bottleneck Identification

The bottleneck identification process utilizes data on freeway operating conditions to determine the location and time of bottleneck activation. Most operating agencies use the *average speed* as the performance measure for identifying bottlenecks. Typical speed thresholds range from 45 to 30 mph. Other approaches use traffic density or detector occupancies and traffic volumes.

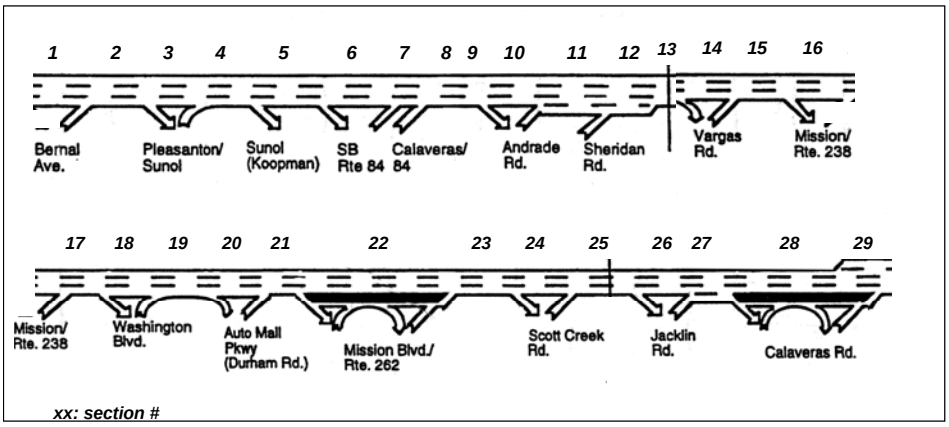
Conventional Approaches

Field data requirements include average speeds along the freeway section collected using floating cars, densities using aerial photographs and traffic counts collected at selected locations. The field data are processed as follows to identify bottlenecks and their impacts.

a) Contour plots: construct speed contour plots based on the field data. Figure 2.1A shows a freeway section consisting of 29 segments. Figure 2.1B shows a contour plot of speeds collected at the section through floating cars during the am peak period. 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). In this example the speed of 35 mph is used as the criterion for bottleneck identification.

Density contour plots also could also be used with typical thresholds of 40-45 veh/mi/lane to identify bottlenecks. Density values are obtained from aerial photographs of the study section taken at successive time intervals. The traffic demand at the bottleneck location can be estimated from the density contour plots assuming a value for the density at capacity (optimum density).

Note that this method cannot 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.



A. I-680 SB

I-680 SB Tach Runs Speed Contour Plot

Interval End	Section number 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

B. Speed Contour Plot Based on Floating Car Data

Figure 2.1 I-680—Bottleneck Identification

b**) Cumulative count curves ("N curves"):** Cumulative curves of flow vs. time are constructed at successive locations along the freeway section (Figure 2.2). The original N curves are shifted horizontally by the average free-flow trip time from their respective locations to the most downstream measurement location. The vertical differences between the curves are excess vehicle accumulations, which indicate bottleneck activation. Each N curve may be rescaled by subtracting a "background count" (corresponding to the average flow rate) to better visualize the excess accumulations. The maximum flow rate before the bottleneck activation, and the queue discharge rate can be determined from the slope of the cumulative N curves. Figure 2.3 also shows the reduction in discharge flow following the bottleneck activation ("capacity drop").

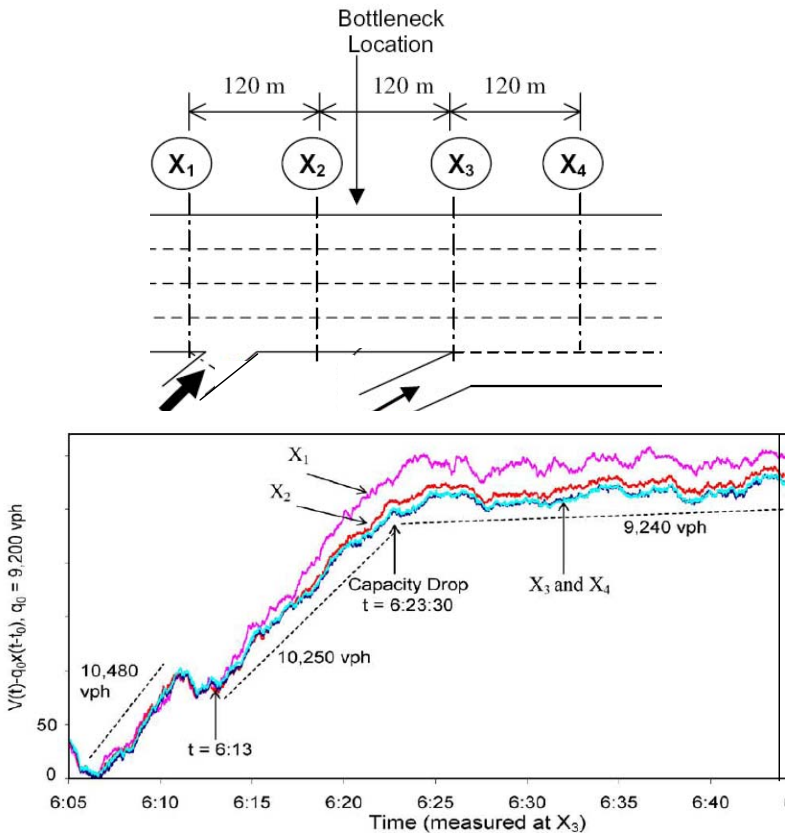


Figure 2.2 Use of Cumulative Count Curves for Bottleneck Identification

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. The average vehicle speeds and densities are calculated from the flow and occupancy detector data assuming an "effective" vehicle length (or *g factor)*, consisting of the average vehicle length plus the detector length:

$$k = \frac{52.8(\%OCC)}{g} \qquad v = \frac{Qg}{52.8(\%OCC)}$$

Where:

k = density (veh/mile/ln)
v = speed (mph)
g = effective vehicle length (average vehicle length plus detector length) (ft)
Q = flow (veh/hr/lane)
%OCC = percent occupancy

The speeds can also be measured directly from two closely-spaced detectors (e.g., double loops –speed traps). Occupancy values below 10% indicate free-flow conditions, whereas values approaching 100% indicate stopped traffic (jam density). Typically occupancy values between 20-25% are the thresholds between free-flow and congested conditions (corresponding to critical density of 43-45 veh/mile/lane).

The surveillance data are aggregated across all-lanes in 5 minutes periods, and are typically used to identify bottlenecks as follows:

a) **Contour plots of speeds or occupancies**. Figure 2.3 shows a contour plot of vehicle speeds on a section of I-880 freeway for the am peak period (5:00-10:00 1m). The plot shows the presence of a bottleneck at postmile 3. The bottleneck is active for about two hours (7:00 to 9:00 am) and the queue is approximately three miles long. This plot is similar to the plot shown in Figure 2.1B. The main difference is that the data in this plot are from all vehicles in 5 minute intervals as opposed a sample of vehicles every 15 minutes.

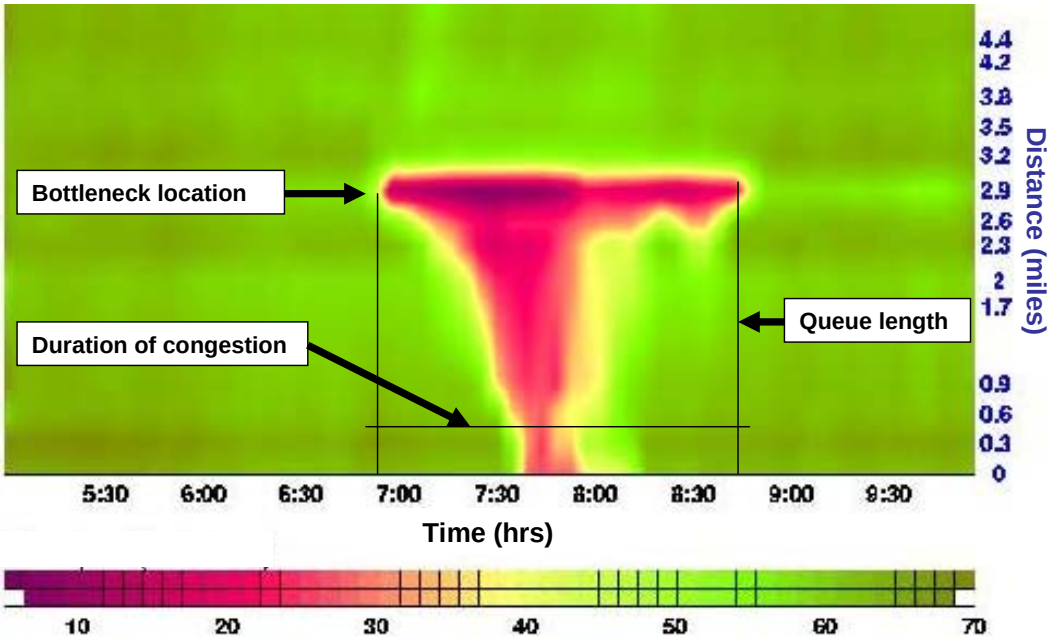


Figure 2.3 Speed Contour Plot from Detector Data (Source: PeMS system [1])

b) **Speed-distance profile**: Figure 2.4 shows a speed-distance plot for the freeway section at time 8:30 am. The plot shows that there is an active bottleneck located approximately at postmile 23. Note the slow speed upstream of the bottleneck location and the increase in speeds past the bottleneck location. The plot also shows that the length of queue is approximately 5 miles long.

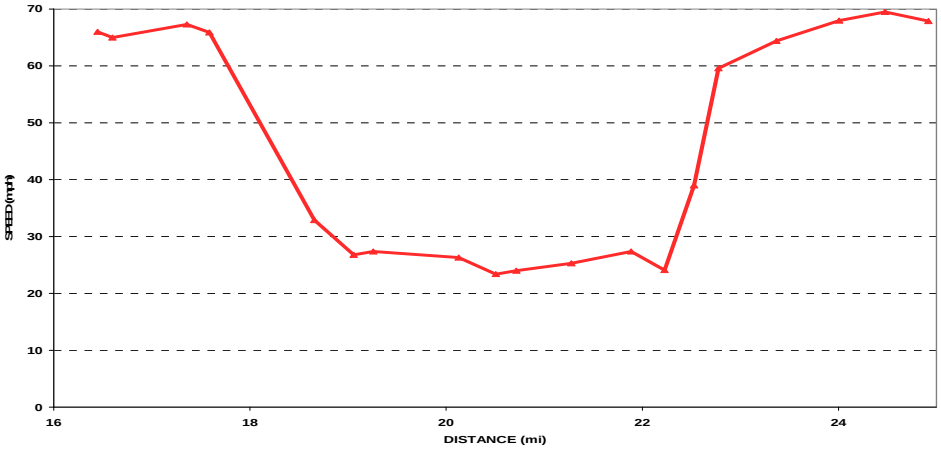


Figure 2.4 Speed-Distance Plot from Detector Data (Source: PeMS system [1])

c) **Time-series plots:** construct plots of occupancy (or speed) data vs. time at successive detector locations. The bottleneck is located in the freeway segment with high occupancy (density) and low speed values at the upstream detector location, and low occupancy and high speed values at the downstream detector location, as shown in Figure 2.5. There is a sharp increase in the occupancy value at the upstream detector (labeled LP 400682) at time 7:30 am indicating the onset of congestion. The downstream detector LP 400983 located approximately 0.6 miles downstream maintains a low occupancy. This indicates that a bottleneck exists between the two detector stations, and remains active for about two hours (from 7:30 to 9:30 am).

Note that the data must be carefully aggregated and analyzed to avoid erroneous bottleneck identifications because of random fluctuations in the occupancy values.

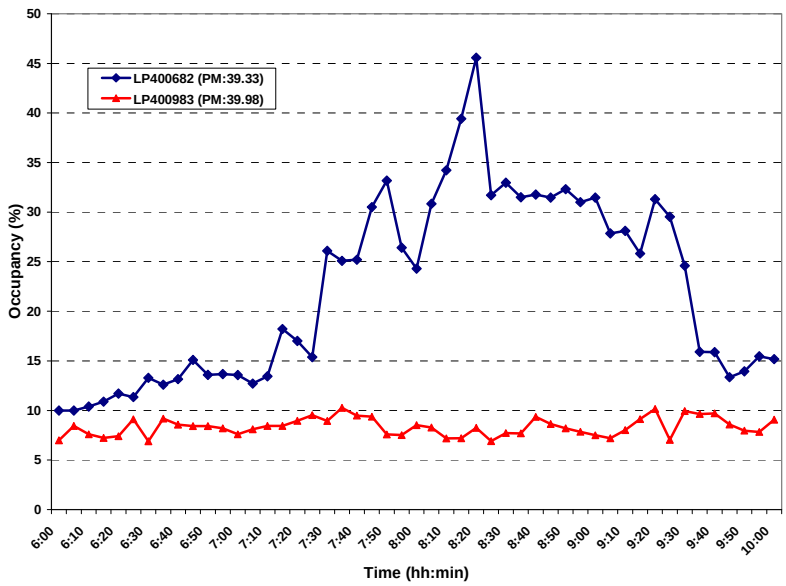


Figure 2.5 Time-Series Plot of Detector Data (Source: PeMS system [1])

Bottleneck Identification Algorithm Based on Surveillance Data

This algorithm attempts to identify bottlenecks on the freeway system at every detector (where "detector" is a set of mainline lane sensors in a single direction). The algorithm processes the surveillance data to determine if the following conditions are met:

- 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. In reality, the bottleneck lies between the two detectors locations. As a matter of simplicity, the bottleneck location is at the detector where the speed has dropped.

For each location (detector) where a bottleneck is activated, the algorithm computes the following statistics for each analysis period (AM, noon and PM periods):

- **Bottleneck duration**: How long the bottleneck was active during that particular shift on that day.
- **Bottleneck (spatial) extent (queue length)**: For each 5-minute period when the bottleneck was active, 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 the sum of the individual segment delays for the entire duration and spatial extent of the bottleneck. The segment 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).

The algorithm was implemented into the California's freeway performance measurement system (PeMS) [1] which collects, stores and processes real-time surveillance data from over 30,000 detectors on California freeways. PeMS includes numerous plots and statistics on freeway performance measures. The bottleneck algorithm implementation algorithm into PeMS also provides a "bottleneck map" showing the location of the bottleneck(s) that have been identified by the algorithm and performance measures (Figure 2.6). The size of the dot drawn for a detector is a function of the number of days that the bottleneck was active, and the color is a function of the average queue length.

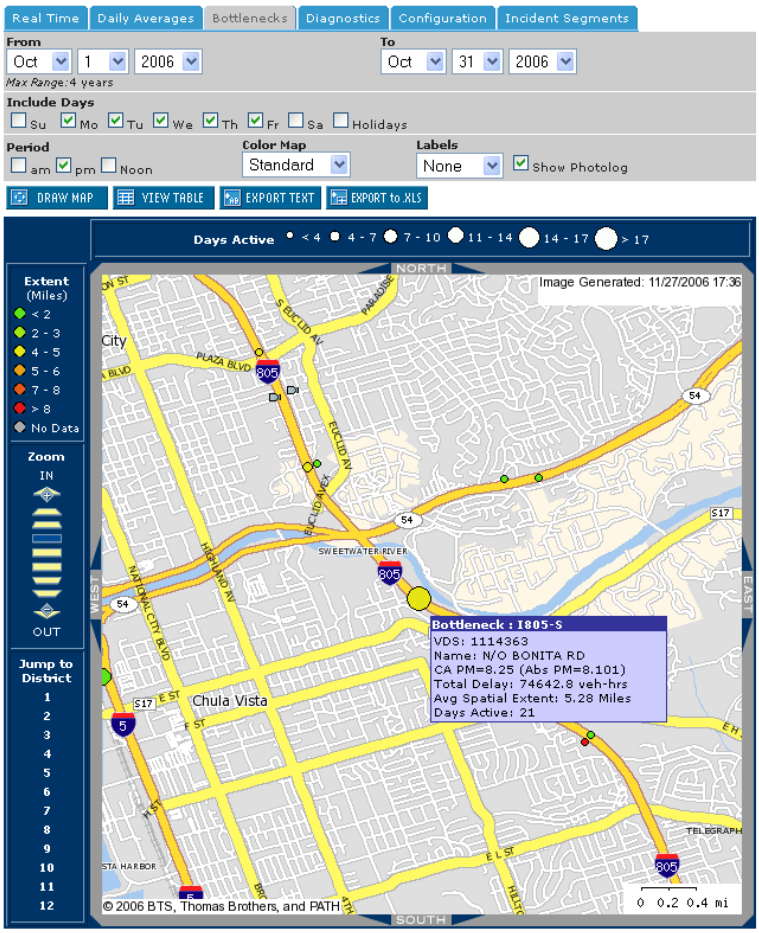


Figure 2.6 Bottleneck Identification Algorithm--Map View

2.3 Bottleneck Causes

Recurrent freeway bottlenecks occur wherever there is either a surge in demand or a restriction in the capacity.

Capacity restrictions:

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
- Horizontal curves where vehicle paths may cross into the next lane
- Long upgrades, particularly in the presence of heavy vehicles
- Narrow lanes on older freeways
- Lateral obstructions which reduce FFS, particularly on bridge sections

Demand surges:

Demand surges occur at the freeway on-ramps. This is the primary cause of freeway bottlenecks in most areas. Furthermore in large metropolitan areas traffic demand tends to exceed the available capacity in most of the highway system during the peak periods. In such situations, the problem is systemic and cannot be specifically tied to demand surges at any single location.

Bottlenecks may also occur when queues on freeway off-ramps spillback onto the freeway mainline, because of heavy traffic off-ramp traffic and insufficient capacity at the downstream end of the off-ramp. 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.

2.4 Bottleneck Classification

Recurrent freeway bottlenecks can be classified 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 freeway section. There are two approaches to addressing Type I bottlenecks: local facility scale demand management techniques (e.g., ramp metering) and strategies to address system-wide problems of demand exceeding capacity.

Type II bottlenecks occur where there is a change in the freeway geometry, and sections of the freeway upstream and downstream have higher capacity than the specific bottleneck section. In such situations limited low-cost capacity improvements through the bottleneck section can be effective. Examples include adding auxiliary lanes, use of shoulders as travel lanes, and restriping to add narrow lane(s).
Type III bottlenecks – which occur mostly in weaving sections – are combination of demand surge with a capacity reduction associated with intensive mandatory lane changing. Mitigations measures include a

combination of demand metering and capacity enhancements. Another example of Type III bottlenecks are diverge bottlenecks, when queues on freeway off-ramps spillback onto the freeway mainline. Such bottlenecks are caused by heavy off-ramp traffic and/or insufficient capacity at the downstream end of the off-ramp (e.g., short green time at the traffic signal controlling the off-ramp traffic). Potential solutions involve freeway capacity enhancements such as adding auxiliary lanes, ramp widening and adjusting the signal timings at the traffic signal controlling the off-ramp traffic.

Figure 2.7 below shows a bottleneck classification scheme, derived from the type I, II, III classification scheme.

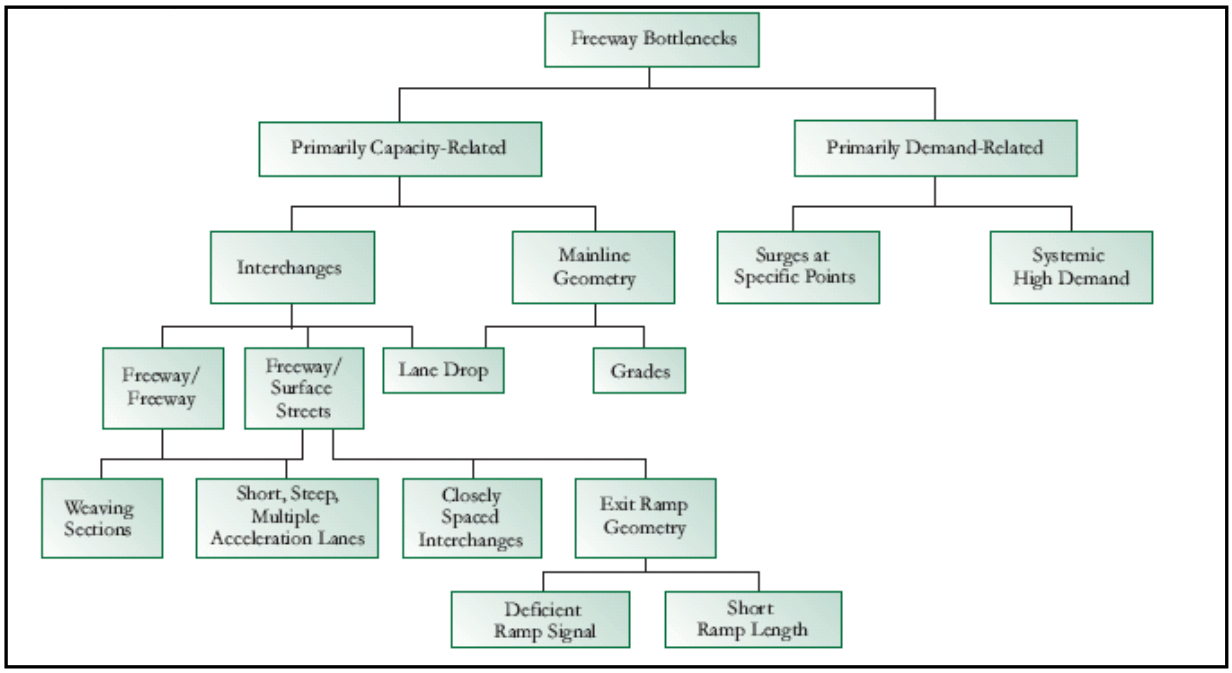


Figure 2.7 Bottleneck Classification (Source: FHWA Bottleneck Primer [2])

2.5 Performance measures:

The performance measures for bottleneck analysis and evaluation of improvements include system measures (primarily related to freeway facility operation), and user measures (primarily related to traveler experience).

System measures

- Throughput (veh/hr): the maximum discharge flow through the section. Veh-miles of travel (VMT) is also used as a throughput measure.
- Queue length (mi): average and maximum length of queue
- Extent of congestion (hrs): duration of queues

Figure 2.8 shows the relationship of throughput expressed in VMT (system output) vs. the total vehicle hours of travel spent (VHT) (system input). It is clearly shown that following the onset of congestion the VMT is reduced despite the significant increase in VHT.

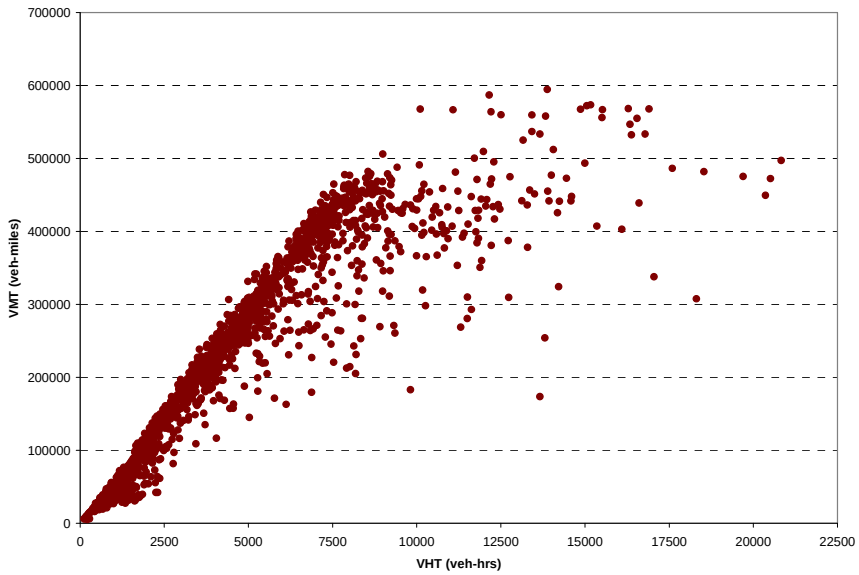


Figure 2.8 VMT vs. VHT –Freeway Sections with Bottlenecks

User measures

- Average speed (mph) or average travel time (min)
- Delay: difference of actual travel time and free-flow travel time
- Travel time reliability metrics:
  - Standard deviation of travel times,
  - Buffer time (min): the difference between the 95% travel time to the average travel time
  - Buffer time index (BTI): the ratio of the buffer time to the free-flow travel time.

Figure 2.9 below the relationship between the congestion level, expressed by the ratio of the actual travel time to the free-flow travel time (called travel time index TTI) to the reliability metric expressed by the buffer time index (BTI). The higher the level of congestion the more unreliable the travel times are in the corridor of interest.

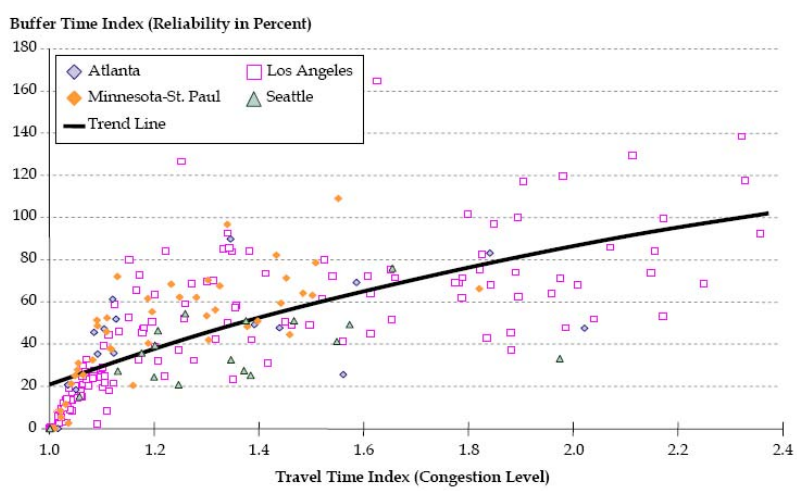


Figure 2.9 Travel Time Index (TTI) vs. Buffer Time Index (BTI) [3]

2.6 Analysis Tools

The analysis tools for identification of recurrent bottlenecks and the evaluation of the low-cost bottleneck improvements 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 (HCM) analyses

The key factors that affect the choice of modeling techniques for analysis of freeway bottlenecks include:

- The perceived cause(s) of the freeway bottlenecks in question; type I bottlenecks (those caused by local or system-wide demand surges) are best analyzed using simulation models or other corridor-level analysis tools that can model the interactions between 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 HCM methods in combination with field observations.

- The facility design characteristics and the type of improvements to be analyzed; microscopic simulation models are appropriate for corridors with complex geometric design features, improvements involving real-time control or other Intelligent Transportation Systems (ITS) measures, and large re-distributions of traffic demand which necessitate analysis using origin-destination matrices.

- Software costs, data requirements and level of effort to apply the analysis tools. Microsimulation models in general require additional data and effort to apply compared to macroscopic analysis procedures.

FREEVAL and VISSIM are the analysis tools applied in the case studies of the NCHRP 3-83 project. FREEVAL was chosen because it is a macroscopic analysis tool that implements the Freeway Facilities methodology in HCM2010. VISSIM was selected because microsimulation is increasingly used in bottleneck analyses. Tables 2.1 and 2.2 provide information and guidance on the capabilities of the selected models and the resources required for their application.

Bottleneck Identification Algorithm Based on Modeling Tools

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 the VISSIM and other microscopic simulation models for bottleneck analysis. These stochastic 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. Therefore, multiple model runs are required to assess the operating conditions at the study section. 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.

Table 2.1 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 recently added as part of SHRP II L08 Project*
***Capability recently added as part of NCHRP 3-96 Project*

Table 2.2 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

CHAPTER 3
BOTTLENECK IMPROVEMENTS

3.1 Overview of Low Cost Bottleneck Improvements

Mitigation measures for recurrent bottlenecks can be classified into a) geometric improvements consisting of permanent modifications to facility design, b) operational improvements designed to manage the traffic demand, and c) active traffic demand management (ATDM) measures that use technology for dynamic capacity enhancements and/or demand management.

Geometric:

- Auxiliary lanes connecting short segments (1/4 mile) of on and off ramps
- Removal of freeway weaving from the mainline to parallel connector-distributor (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)
- Re-striping to add HOV lane within existing ROW (no new construction)
- 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

Overall, the addition of auxiliary lanes appears to be the most widely used geometric improvement for recurrent bottlenecks. However, 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. Implementing agencies may need to educate the driving public on their use.

The addition of lanes through lane width reductions and/or restriping may not be feasible in several areas because many of these opportunity locations have already been converted, and there is now a hesitancy to use in additional locations because of safety concerns.

Addition of HOV lanes either through restriping or through a lane addition is a popular measure especially at fast-growing areas because they address the congestion problem from both the supply and demand side. 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.

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

These bottleneck improvements address the traffic demand and preserve the capacity of the freeway. They are mostly implemented in areas with systemic high demand with multiple bottlenecks that local design improvements tend to move the bottleneck problem to a downstream location.

Active Traffic and Demand Management

- Hard Shoulder Use
- Plus Lane
- Variable Speed Limits

These measures are concerned with dynamic capacity enhancements at bottleneck locations using intelligent transportation systems (ITS) technologies. 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 3.1 below illustrates an example of dynamic cross section applications in Netherlands.

The use of variable speed limits (VSL) on freeways aims to reduce the difference of individual vehicle speeds on the freeway mainline, create smoother traffic flows and reduce the probability of flow breakdown. Case studies reported significant reductions in the number of accidents, but not systematic improvements at bottlenecks.

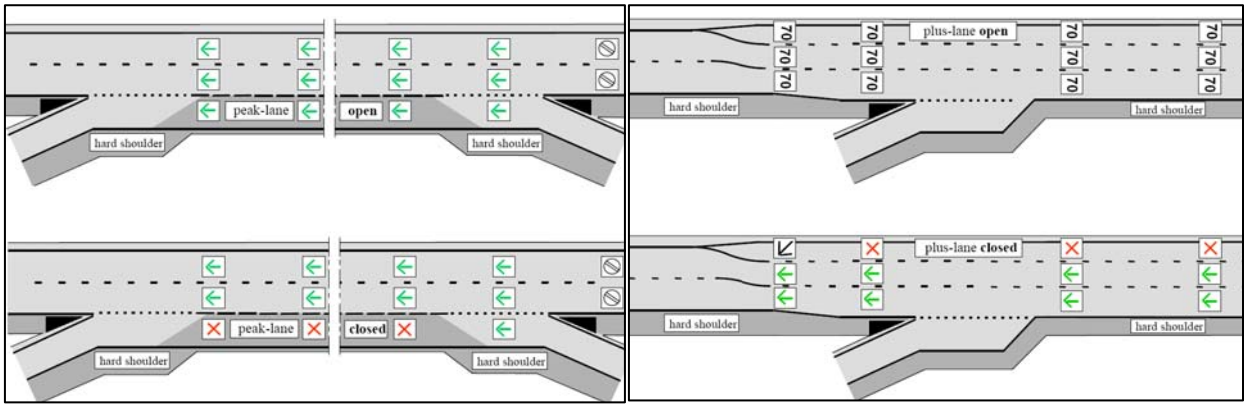


Figure 3.1 Peak Lane and Plus-Lane Design in the Netherlands [4]

3.2 Mapping Bottleneck Types to Mitigation Measures

Table 3.1 below shows a matrix of common bottleneck causes to potential low-cost improvement measures.

Table 3.1 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

In general 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 is a useful strategy when reasonable alternative routes exist.

The selection of the mitigation measure(s) should be based on careful analysis of alternatives and the cost-effectiveness of the proposed improvements particularly if multiple bottlenecks are present in the study section. This is illustrated for the example test section of I-680 freeway originally shown in Figure 2.1A. The speed contour plot (Figure 2.1B) provided initial guidance on locations to add auxiliary lanes to remove bottlenecks. Figure 3.2 below shows the results from the evaluation of adding auxiliary lanes at selected segments of the freeway section. The horizontal axis in Figure 3.2 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 indicate that adding auxiliary lanes on sections 28, (28+21), and (28+23) would produce the highest benefit/cost ratios. Note that the benefits of 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.

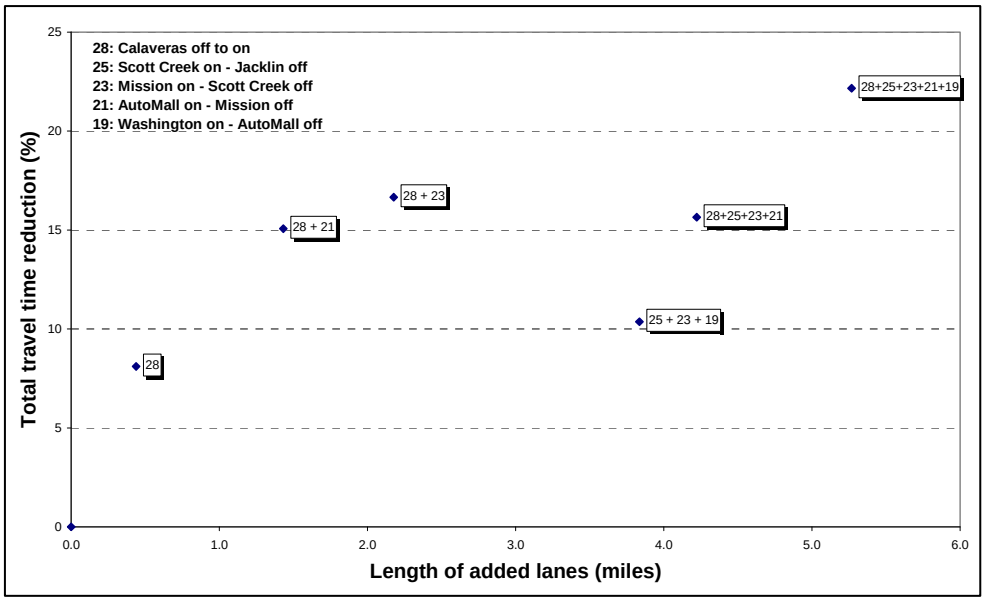


Figure 3.2 Comparison of Alternative Auxiliary Lane Configurations—I-680

The development of mitigation measures should carefully consider the system-wide impacts on the freeway under investigation, as well as the possible impacts to the adjacent network of highways and arterial streets. 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. An example is shown below in Figure 3.3 [5].

In case I, the active bottleneck is at location B. The upstream total demand is 6,000 vph, and the discharge flow rate is 5,500 vph. The total outflow at location A is 5,950 vph. Local improvements result in the bottleneck removal at location B, and the outflow is 6,000 voh. However, this results in activation of bottleneck at location A with discharge flow of 5,500 vph. Therefore, the improvement at location B resulted in a net reduction of the system outflow of 450 vph.

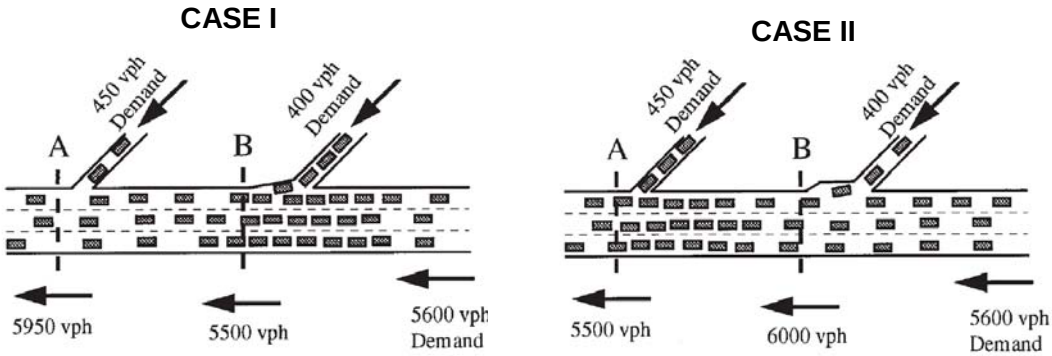


Figure 3.3 Impact of Hidden Bottlenecks [5]

3.3 Benefits and Costs of Bottleneck Improvements

The findings from the literature, interviews with operating agencies and the case studies show that low-cost bottleneck removal measures result in significant benefits in terms of increased throughput and delay reductions. Even modest travel time improvements in heavily congested sections have a positive effect son mainline travel time reliability and safety.

Reported costs for bottleneck improvements range from $8,000 (for restriping projects) to around $2.5 million (for adding auxiliary lanes). Benefit/Cost ratios ranged from 9:1 to 400:1. Ramp metering is considered very inexpensive if the equipment is already installed and the intervention involves the adjustment of the metering rates. Costs are higher if surveillance and communications systems are installed for traffic responsive ramp metering strategies. Ramp metering installation project costs are generally in the range of $100,000 to $250,000 per entrance ramp. These costs do not include the costs of reconfiguring and lengthening on-ramps to add storage space.

3.4 Funding and Programming of Bottleneck Initiatives

The findings from the literature and the interviews with operating agencies show that the most active operating agencies at programming and funding low-cost bottleneck improvement projects are also those that have developed and engaged in partnerships with transportation stakeholders. 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 interviews conducted here suggest that there are three (not mutually exclusive) ways to garner funding for these underappreciated yet effective 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. Examples include the Maricopa Association of Governments (Phoenix, Arizona) and the Southeastern Michigan Council of Governments (Detroit, Michigan) metropolitan planning organizations that include integrated bottleneck identification and analysis into their planning processes to ensure that both short and long-term funding are available for bottleneck improvements
- Creating a stand-alone low-cost bottleneck funding program.

Examples of approaches and funding programs for bottleneck improvements include:

- 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

PROCEDURES FOR APPLICATION

4.1 Problem Definition

Selection of the study area

The spatial and temporal boundaries of the study area should be selected considering all possible analysis scenarios to be investigated, for both existing and projected conditions. The selection of the study area is based on several factors including the stakeholders' objectives and priorities, perceived causes and impacts of congestion, relation wit ongoing planning and operations studies, and funding constraints.

An important consideration is whether only the freeway will be analyzed, or the adjacent arterial network will be included in the analysis (freeway corridor study). Freeway corridor studies are more complex and require much higher level of effort than freeway only analyses, depending on the number of parallel and crossing arterials included in the study area. For example, freeway corridor studies require geometric data for all arterials and the freeway, control data for the ramp meters and the signalized intersections, and network-based origin-destination data for each time interval. The remainder of the document assumes a freeway operational analysis study (adjacent facilities are not considered.

The freeway study section boundaries should be carefully selected to include both the spatial and temporal extent of the congestion. Congestion should not extend beyond the upstream end of the freeway study section nor should a bottleneck occur downstream of the study section that causes congestion to occur within the study section. Congestion should not occur before the study duration beginning time nor extend beyond the study duration ending time. The selection of the study boundaries should also consider the analysis with projected demands under the existing design ("no build scenario"). If the projected increase in traffic demand causes congestion to extend beyond the upstream study section boundary, or to occur before or after the study duration time, then the performance analysis of this scenario and comparisons with other scenarios will not be correct.

4.2 Data Requirements and Sources

Data requirements for bottleneck analyses include input data for the application of the analysis tools and performance data for the assessment of operating conditions along the corridor, and calibration of the modeling tools. The data requirements depend on the study area selected, time periods of analysis (existing and/or projected conditions), and alternatives to be analyzed.

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 data are collected using manual techniques, e.g., manual counts 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 level of effort and cost for data collection and processing largely depends if a data archival system is in place that can store and process real-time surveillance data.

Input data for the application of the modeling tools include supply data, traffic demand data, and control data:

Supply data

Supply data consist of the location and spacing of freeway on- and off-ramps, acceleration & deceleration lanes, number of lanes on each freeway segment, HOV lanes design such as location and access points, location of lane drops (or additions), auxiliary lanes, lane widths, lateral clearances, horizontal and vertical alignments. It is important that the data should be verified in the field instead of relying on office drawings that usually are out of date. In the case of data archival systems, most of this information is available in the TMC configuration files in electronic format. Also, most of this information can be extracted from on-line maps available on the internet.

Demand data

Traffic demand data consist of freeway entry and exit counts (typically at 15 minute time intervals), classification counts (to determine proportion of vehicle types) and vehicle occupancy distributions (proportion of vehicles with single passenger, two passengers, and three or more passengers).

It is important that the field-measured entrance counts expressed as flow rates represent traffic demands. Therefore, the measurement location at each freeway entrance (freeway mainline input and at each on-ramp) should be selected where queues (congestion) do not occur. Similarly, the location for measuring exit counts should be selected where queues do not occur. Note that these exit counts do not represent demands if upstream freeway congestion occurs, due to the presence of bottlenecks but they can be adjusted through the use of *scale factors*.

Scale factor is defined as the ratio of the total number of entering vehicles o the total number of vehicles that exited per time interval. The value of scale factor under incident free traffic conditions ranges between 0.90 to 1.10 with a mean value of close to 1.00 over a 5-h period peak period. As congestion builds up the scale factor is greater than 1.00, and becomes less than 1.00 as congestion dissipates.

Control data

Control data include ramp metering rates and operation of HOV lanes if any (hours of operation, minimum number of vehicle occupants allowed to use the HOV facility), operation of high occupancy toll (HOT) lanes if any (toll rates and schedule). Additional data on ITS field elements may be required depending on the mitigation measures to be analyzed. Examples include data on location and type of changeable message signs, types of messages displayed, speed limits and truck restrictions. Most of the control data are typically stored in the TMC database so no additional manual data collection effort is required. Also data on signal settings at signalized intersections at off-ramps if any.

Performance data

Performance data for the assessment of existing operating conditions on the study section include average travel speeds (travel times), discharge flows at freeway bottlenecks and queue lengths. Also queue lengths if any at each on- and off-ramp. These data are used to identify the location of existing active bottlenecks and to calibrate the analysis tools prior to the evaluation of alternative improvements. Most of such data will also be used in the field evaluation of the mitigation measures, so they have to be collected “before” and “after” the implementation of the bottleneck improvements.

Additional data on performance measures may be collected depending on the objectives of the study and the stakeholders’ priorities. Examples include travel time reliability metrics (travel time distribution and related statistics), and safety related measures (number and severity of accidents).

Need for Multiple days of data

It is known that traffic demands vary by day the week and month of the year. The variation in traffic demand may have significant impacts on traffic performance especially in congested traveled freeway facilities. It is recommended to collect a minimum of five weekdays of data under incident free conditions; each weekday's data should reflect a time period starting before the typical am peak and continuing through the end of the pm peak period (e.g., 5:00 am through 8:00 pm) in order to determine the beginning and duration of the peak periods based on field measurements.

Figure 4.1 illustrates the impact of demand variation on the spatial and temporal extent of the congestion. The Figure shows speed contour plots for the I-210 freeway section for three weekdays (typical, heavy and light). The demands in the heavy day are 5% higher than the typical day. This results in a 25% delay increase, and queues present after the end of the morning peak period. Less than typical day demands (light day) result in faster dissipation of congestion.

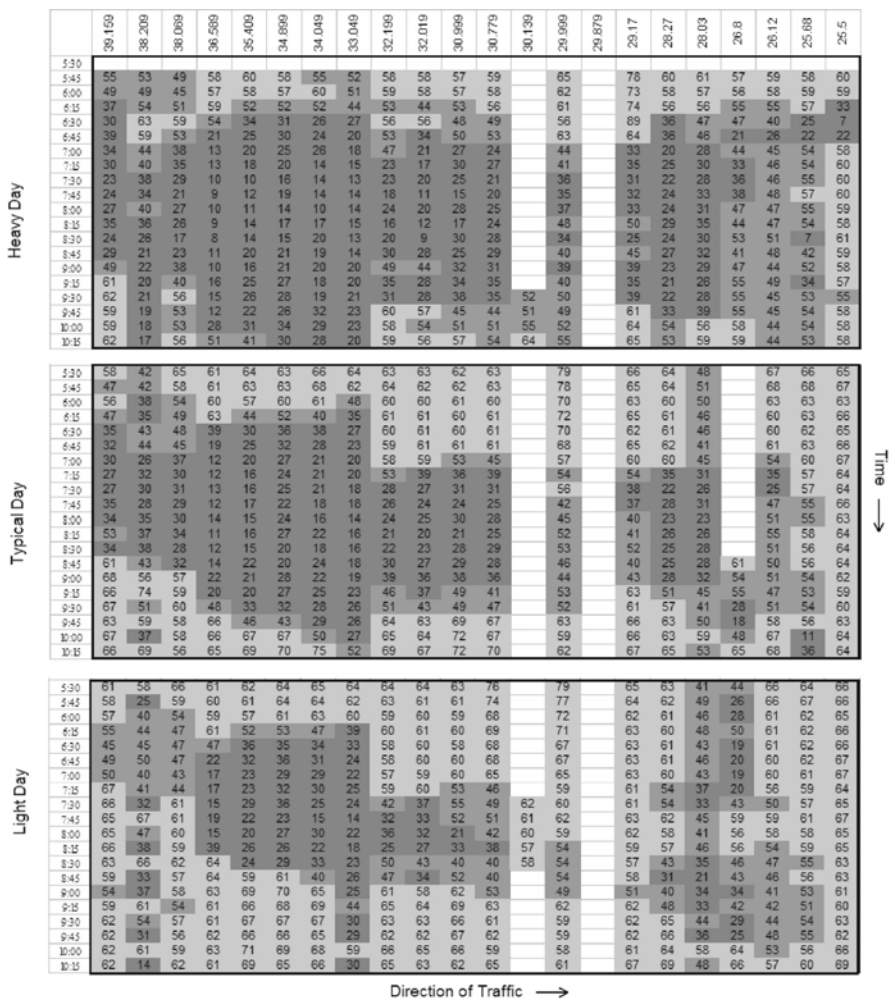


Figure 4.1 Impacts of Demand Variation—I-210

Data Sources

Manual data collection for freeway analysis projects is expensive and time consuming; often limited time and budget for manual data collection results in only one day of data, which may not provide an accurate representation on freeway operating conditions due to the demand variation. A surveillance system and a data archival system in place that can continually collect, store and process data on the freeway operating conditions

The choice of data collection methodology by a state DOT also depends on the costs involved to implement a surveillance system and the potential uses of the data for other purposes in addition to bottleneck analyses. Typical costs for the installation of a loop detector station covering four freeway lanes is about $25,000 (Caltrans estimates). This translates to about $50,000 for detection costs per directional freeway mile (assuming detectors are spaced 0.5 mile apart). Additional costs include communications (which vary widely depending on the communications equipment and use), and the capital, operating and maintenance costs at the TMC. If the sole use of the real-time data would be to identify bottleneck locations then the costs may be too high compared to manual data collection, which is labor intensive but has low equipment capital, operational and maintenance costs. In most metropolitan areas, however, real-time data are used for several purposes (incident management, ramp metering, traveler information etc), so their use in bottleneck analyses involves minimum additional costs.

4.3 Analysis Framework

Figure 4.2 shows the 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.

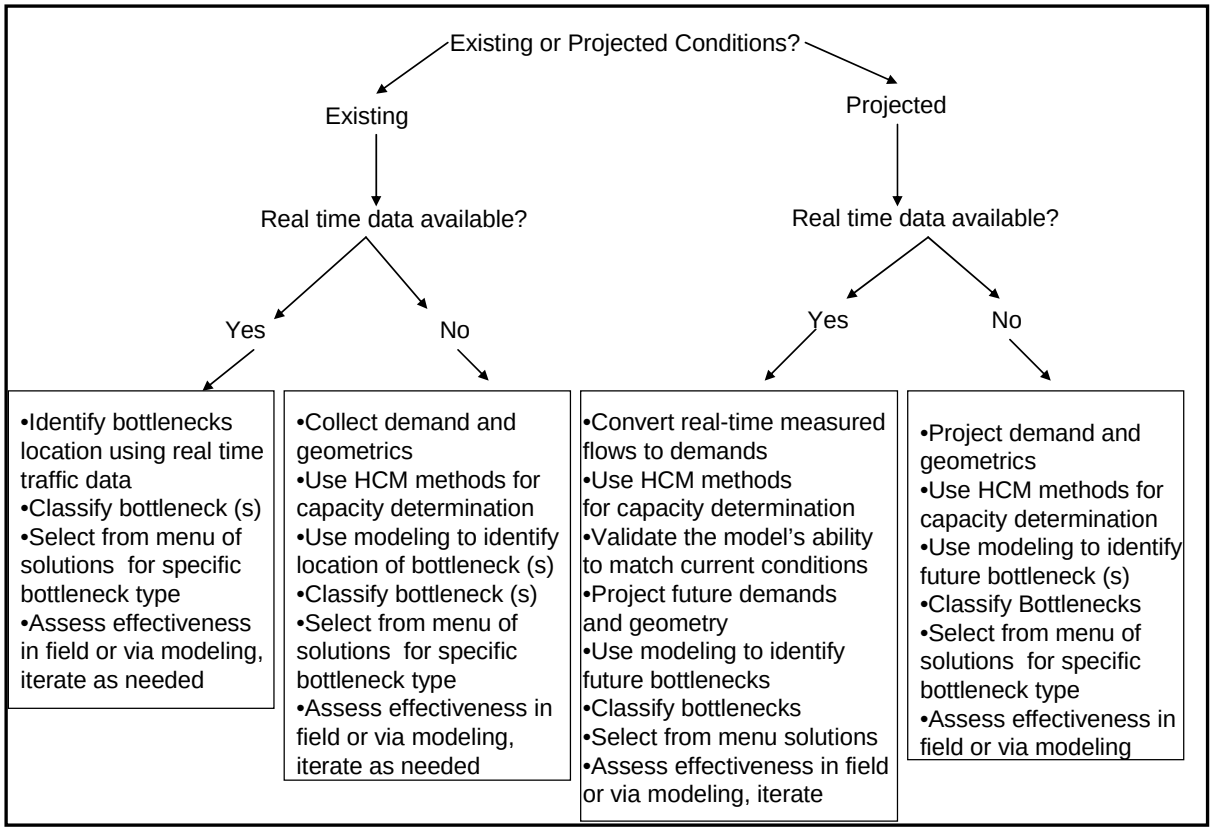


Figure 4.2 Framework for Analysis of Freeway Bottlenecks

4.3.1 Case I: Existing Bottlenecks – Real Time Data Available

A. Bottleneck identification

Identify the bottlenecks in the study section based on the real-time data processing procedures and algorithm described in Chapter 2.

B. Determine cause(s) of bottleneck

Determine the cause of bottleneck occurrence 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 on-ramp demands, ramp metering rates and HOV lane operations if any.

C. Develop solutions

Appropriate low-cost solutions are selected based on the bottleneck type and the characteristics of the study area based on Table 3.1. The solution may be a single improvement or a combination of mitigations. For example, possible improvements to a bottleneck caused by a weaving section include restriping to allow an additional exit lane at the off-ramp and metering of the on-ramp.

D. Assess proposed solutions and select the preferred mitigation measure(s)

The assessment of the proposed solutions and selection of the preferred mitigation measure(s) is an iterative process based on the stakeholders objectives and constraints and the following technical considerations:

> **Estimated benefits at the bottleneck location**: these include removal of bottleneck, higher travel speed and discharge flow, reduction in queue lengths.
>
> **Impacts to the freeway and arterial network:** improvements in the selected MOEs for the entire study section, possible appearance of hidden bottlenecks, and impacts to the adjacent network, in terms of excess queues to the surface street system because of ramp metering.
>
> **Costs of implementation**: capital, operating and maintenance costs of the selected bottleneck improvements

The analysis of alternatives must consider both the absolute and relative magnitude of the estimated improvements in the performance measures (MOEs). Predicted benefits of 2% in MOEs may not be realized in the field following implementation. At the same time large percentage improvements may not translate to actual benefits because of the overall traffic levels. Also, highly oversaturated conditions in the baseline (existing) conditions result in over-estimate of the benefits.

Discussion

Real-time data alone cannot be used to assess the effectiveness of low-cost bottleneck improvements prior to implementation; therefore, a modeling tool is required to assess the proposed improvements prior to field implementation, and to analyze possible hidden bottlenecks and the impacts to the freeway and arterial network. Real-time however can be readily used to provide the input data to the analysis tool and the performance data to calibrate the model. The steps for the model application and calibration are described in Section 4.3.2 below.

Real-time data can be used to evaluate the effectiveness of bottleneck improvements following their field implementation (“before” and “after” studies). Figure 4.3 shows the improvement in the freeway mainline speed on I-580 EB following the implementation of ramp metering, based on loop detector data.

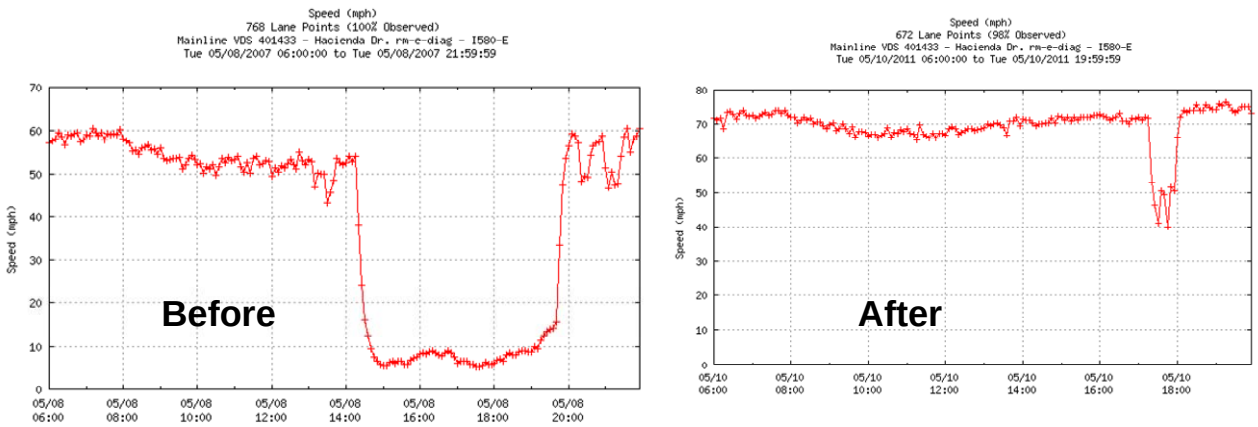


Figure 4.3 Impact of Ramp Metering – Mainline Speed I-580 EB

4.3.2 Case II: Existing Bottlenecks – No Real Time Data Available

A. Bottleneck identification

Collect data on freeway geometrics, traffic demand, and control data, and data on traffic performance. Typically, speeds are collected through floating cars equipped with in-vehicle data loggers (or laptop computers) to automatically record travel speeds. Floating car runs are typically made at 15 min intervals. Process the data in the form of contour plots (Figure 2.1B) or speed-distance profiles (Figure 2.4) to show the location of active bottleneck(s) and congestion patterns on the study section.

Calculate the capacity of each segment in the freeway study section using HCM2010 procedures.

Use an analysis tool to determine the bottleneck location(s), and impacts.

Selection of the analysis tool: Tables 2.1 and 2.2 provide guidance for selecting the model to perform the bottleneck analysis, considering the model capabilities and features, range and type of improvements to be tested, and the resources required for model application

Model calibration: It is essential that the model is calibrated prior to the analysis of alternative improvements. Calibration involves the adjustment of the model parameters so that predicted performance reasonably matches observed operating conditions in the study section. The recommended three-step calibration process was developed as part of FHWA Traffic Analysis Toolbox [6]:

- **Calibration for capacity:** compare model estimates of capacity with field measurements taking on freeway bottlenecks; Note that for the FREEVAL model the capacity input are HCM2010 based; for VISSIM or any other microscopic model capacity is a derived outcome of the car-following and lane changing algorithms and their parameters that are imbedded in each model. 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.

- **Route choice calibration:** compare model predicted volumes with actual traffic counts taken at representative links of the network (this step is not required for modeling of freeway only sections)
- **System performance calibration:** Compare model predicted travel times, plus spatial and temporal extent of queuing on the freeway with field data, e.g., speed-contours collected with floating cars.

  The availability of real-time data can assist in the calibration of the analysis tool. Figure 4.4 below shows a comparison of the model predicted vs. measured densities (derived from the loop detector occupancies) on the I-210 freeway. Note the close agreement between observed and simulated values. Also note the gaps in the detector data because of detector failures.

Detector data

	39.159	faulty 38.209	faulty 38.069	36.589	35.409	34.899	faulty 34.049	33.049	32.199	32.019	30.999	faulty 30.779	faulty 30.139	faulty 29.999	faulty 29.879	29.17	28.27	faulty 28.03	faulty 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	53	-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

Model

	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	56	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

Figure 4.4 Measured vs. Predicted Density Contours—I-210

Use the criteria in Section 2.6 to identify bottlenecks based on the model outputs. Note that requirement for multiple model runs in the case of stochastic microscopic simulation tools.

B. Determine cause(s) of bottleneck

The process is the same as described in Section 4.3.1B.

C. Develop solutions

The process is the same as described in Section 4.3.1C.

D. Assess proposed solutions and select the preferred mitigation measures

The process is the same as described in Section 4.3.1D.

4.3.3 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) described in Section 4.3.2 with the following important differences:

- Projected 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.
- Projected data on freeway geometrics may involve modification of existing facilities or new facilities (e.g. proposed freeway interchange as part of land development)
- 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. Because there are existing bottlenecks in the study area, calibration is based on traffic performance (speeds or travel times). Capacity estimates may be approximately obtained through overloading a segment in the simulation and observe in the output the maximum output flow.
- The analysis is performed using projected data on traffic demands and existing or geometrics. The location of the projected bottleneck is when the segment demand exceeds the capacity (d/c >1).

4.3.4 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) described in Section 4.3.2 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).

- The analysis should carefully consider the sensitivity of the results to the assumptions used to develop projected inputs especially traffic demands.

REFERENCES

1. http://pems.eecs.berkeley.edu

2. FHWA, "Traffic Bottlenecks: A Primer. Focus on Low Lost Operational Improvements," Report No. FHWA-HOP-07-130, US Department of Transportation, July 2007.

3. Cambridge Systematics, "Guidelines for Effective Freeway Performance Measurement," Final Report and Guidebook for NCHRP Project 3-68, Washington DC, 2006.

4. Stembord, H., T. Van-Den Brink, and B. Hellerman, "Dynamic Cross-Sections: Increased Capacity On Existing Infrastructure," paper presented at the 81st TRB Annual Meeting, Washington DC, 2002.

5. Yagar S., and R. Hui, "Systematic Analysis of Freeway Improvements," Transportation Research Record No. 1954, Journal of Transportation Research Board, 1996.

6. Dowling, R., A. Skabardonis, and V. Alexiadis, "Traffic Analysis Toolbox Volume III: Guidelines for Applying Traffic Microsimulation Modeling Software," Report FHWA-HRT-04-040, Washington DC, June 2004.