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Bottleneck Identification and Calibration for Corridor Management Planning

Xuegang (Jeff) Ban
California Center for Innovative Transportation (CCIT)
University of California - Berkeley
2105 Bancroft Way, Suite 300
Berkeley, CA 94720-383
Phone: 510-642-5112
Fax: 510-642-0910
Email: xban@berkeley.edu

Lianyu Chu*
California Center for Innovative Transportation (CCIT)
University of California Berkeley
522 Social Science Tower
Irvine, CA 92697-3600
Tel: (949)824-1876
Fax: (949)824-8385
E-mail: lchu@berkeley.edu

Hamed Benouar
California Center for Innovative Transportation (CCIT)
University of California – Berkeley
2105 Bancroft Way, Suite 300
Berkeley, CA 94720-383
Phone: 510-642-5224
Fax: 510-642-0910
Email: benouar@calccit.org

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** Corresponding Author*

Abstract:

Corridor mobility improvements require a new approach to corridor management planning and operations. Recent investigations are aimed at improving the safety and efficiency of existing transportation systems by integrating state-of-the-art operational analysis (such as micro-simulation) into more traditional corridor planning. One of the important elements in developing corridor management improvements is better bottleneck analyses. Such analyses play a crucial role in corridor management planning for both performance assessment and simulation model calibration. This paper proposes new approaches for bottleneck identification and calibration in simulation. The former is conducted using percentile speeds based on data from multiple days. It turns out that this is more appropriate for urban congested freeways than using single day data. The algorithm for bottleneck calibration represents the first attempt to rigorously calibrate bottlenecks in micro-simulation. It is a three-step process, including visual assessment, bottleneck area matching, and detailed speed calibration, aiming to calibrate bottlenecks in three levels of detail. Using the I-880 corridor network in the San Francisco Bay Area, it has been shown that the identification method can adequately identify corridor bottlenecks; the calibration procedure complements and improves current practice of simulation calibration.

1. Introduction and Motivation

Traffic congestion and safety issues continue to be increasing concerns of both the traveling public and transportation agencies. Many of the nation's urban corridors experience a considerable amount of congestion every day. Some of the congestion is caused by accidents or unplanned events and some by recurring bottlenecks. Due to the cost of construction, funding availability, and right of way and environmental concerns, many of the congested corridors will not have additional infrastructure built for many years to come. Meanwhile, it is important for transportation agencies and decision makers together at the state, regional, and local levels to invest in existing facilities and collaborate in better managing their multi-modal transportation corridors with improved operational strategies and technology. Because of these challenges, corridor management planning (CMP) and similar concepts have been proposed recently, including the CMP Demonstration by Caltrans (*1*) and the Integrated Corridor Management (ICM) program by FHWA (*2*). CMP integrates advanced operational analysis techniques such as micro-simulation into the traditional planning process. CMP begins by defining how the system is performing, understanding why it is performing that way, and then evaluating different strategies, especially operations centric ones, to address deficiencies. The strategies are then tested using simulation modeling to allow for more accurate estimation of benefits.

Three major components can be identified for CMP: corridor performance assessment, micro-simulation model development, and improvement strategy scenario evaluations. It turns out that bottleneck analysis, including bottleneck identification and calibration in micro-simulation, plays an important role in the study of CMP. Bottlenecks are sections of the freeway that either have capacities less than or demand greater than other sections. These locations will probably experience traffic congestion earlier than other locations as traffic grows (*3*). Bottlenecks have crucial impacts on the performance of traffic corridors and simulation model development in CMP. In particular, it is clear that

- Bottlenecks are an important measure of the corridor system performance;
- Identifying bottlenecks correctly can help develop appropriate improvement strategies to resolve congestion and safety problems; and
- Micro-simulation models need to be calibrated to account for bottlenecks.

As a result, CMP calls for solid and practical methodologies for corridor bottleneck identification and calibration in simulation. Nevertheless, practical methods for bottleneck analysis are sparse in the literature. Many of the methods that are used rely on limited sets of data. For example, in Caltrans, bottlenecks are identified using floating car runs (*4*). This method may not identify bottlenecks accurately for congested urban freeways due to limited runs and day to day traffic variations. Chen et al. (*5*) provided a systematic method to identify freeway bottlenecks based on PeMS data. The method, however, is operated on single day data that may not be appropriate for CMP, especially for simulation model development. This is because CMP needs a simulation model with typical congestion patterns along the whole corridor, but single day data is usually impacted by incidents and day to day traffic variations. Other methods that have been developed to identify bottlenecks rely on large amount of 30-second data to investigate individual bottlenecks. Cassidy and Windover (1995) used 30-second data to construct curves of cumulative vehicle counts and occupancy to obtain the measurement resolution necessary to observe transition from free flow to queued conditions. This method is effective for detailed analysis of features of a recurring single bottleneck. But the method is time consuming to be applied to identifying and analyzing multiple bottlenecks in a corridor. A more automated solution is required first for identifying a bottleneck; then a more detailed analysis is needed to address individual or sets of bottlenecks.

On the other hand, according to FHWA simulation guideline (*3*), visual audit is the primary method for bottleneck calibration. For example, a recent simulation modeling study addressed day-to-day traffic variations by considering speed contours of a heavy, a typical, and a light day of traffic for bottleneck identification and calibration (*6*)˙ However, how to choose a typical day, how to remove the influence of incidents in the data, and how to conduct systematic bottleneck calibration still remain as open questions. Furthermore, to date, no solid measure has been developed for rigorous bottleneck calibrations.

In this paper, we focus on developing practical and efficient approaches for bottleneck identification and calibration. In particular, we aim to identify recurrent bottlenecks that are the most interesting and critical, especially for long corridors with heavy congestion and high incident rate (e.g., the I-880 corridor in the San Francisco Bay Area). First, the bottleneck identification method is proposed based on percentile speed data across multiple days. Percentile speeds are particularly suitable for highly congested urban corridors due to frequently occurred traffic incidents that invalidate the use of single "typical" day data. Based on the Speed Contour Map (SCM) generated from percentile speeds, we show that bottleneck identification can be performed either manually or automatically using elementary matrix manipulations. We further propose a three-step process for bottleneck calibration, as one critical component in the microscopic simulation model calibration process. The first step is a visual assessment based on SCMs to make sure a general match in terms of number and locations of bottlenecks between simulated and observed data. The second step is to match bottleneck areas using a newly developed measure based on binary SCMs. The last step is to calibrate detailed bottleneck speeds. Experimental studies conducted on the I-880 corridor illustrate that the proposed bottleneck identification method can identify appropriate corridor bottlenecks. Further, the three-step calibration method complements and improves the current practice of simulation model calibrations.

This paper is organized as follows. The proposed method for using percentile speeds to conduct bottleneck identification is discussed in Section 2. The advantages of using percentile speeds are also given in this section. Section 3 focuses on the three-step method for bottleneck calibration. A real world example is provided in Section 4 based on the I-880 corridor in the San Francisco Bay Area. Finally, concluding remarks and future study directions are addressed in Section 5.

2. Bottleneck Identification

2.1 Current Practice

A congested freeway may contain bottlenecks and hidden bottlenecks. The former is defined as a location that initiates traffic congestion and the latter is a location that initiates traffic congestion only under a certain demand pattern. The feature of a bottleneck is that its downstream is free flow and its upstream is jammed. Hidden bottleneck is usually located downstream or upstream of a regular bottleneck.

One method to study a bottleneck and its severity is the floating car method. For example, Caltrans has a HIghway COngestion Monitoring Program (HICOMP), which conducts floating car studies for finding traffic congestion patterns of state highways. Floating car runs are scheduled during peak periods and twice a year. Several floating cars are on duty at the same time and trips are generally 15 to 30 minutes apart. Since the current floating car method is based on a limited number of observations, the traffic congestion report generated from the floating car runs may not be able to show congestion accurately. This is especially true for major metropolitan areas where the freeway system may have different day-to-day traffic conditions due to different demand patterns and incidents.

Another widely used approach is to analyze Speed Contour Maps (SCM). SCM is a two-dimensional surface plot on the space-time plane based on time-dependent speeds at several locations along a stretch of freeway. Usually, data can come from a freeway with vehicle detection systems, which collect traffic data continuously. Freeway Performance Measurement System (PeMS), for example, is a system to collect, filter, process, aggregate, and examine loop detector data from freeways in the State of California (*7*). Based on data from PeMS, freeway performance and its bottlenecks can be analyzed manually by users or automatically using its spatial analysis (i.e. speed contour function) and bottleneck analysis tools (*7*, *8*). Usually, to identify accurate recurrent freeway bottlenecks, SCMs from different days need to be analyzed to remove non-recurrent bottlenecks caused by incidents. This is usually performed manually and thus may be time-consuming. More importantly, due to the variation of traffic congestion from day to day, bottlenecks obtained this way may not be reliable.

To overcome deficiencies of previous methods, we present in this section bottleneck identification methods based on percentile speed data. The identification algorithms include both a manual method based on visual assessment and an automatic method.

2.2 Percentile Speed Data

To identify bottlenecks, an SCM based on “representative” speeds needs to be prepared. The speed data we use in this study are obtained from PeMS, which obtains measured speeds directly from double loop systems or estimates speeds for single loop systems. Since PeMS has archived a large amount of speed data (several years) for each freeway detector, how to better utilize these data to obtain “representative” speeds becomes a critical issue. Intuitively, using data from multiple days instead of a single day would be beneficial, but the question is how to generate a “representative” speed from a set of candidate speeds. The average speed might be one option and speed from a typical day is another. However, speed data from the former method may be biased by incorrect speeds from some days (i.e., outliners), while speeds from the latter method may be biased by incidents occurred in the typical day. This paper thus proposes the use of percentile speeds as the “representative” ones.

Denote *i*, $\forall i = 1,2,\cdots,N$, is the index of a freeway detector and *N* is the total number of detectors within the studied portion of freeway. Also denote *t* the discrete time interval (e.g., 5 minutes) $\forall t = 1,2,\cdots,T$ and x_i is the postmile (PM) of detector *i*. Further $v_d(i,t)$ is the speed of detector *i* at time *t* on the *d*-th day for $d = 1,2,\cdots,D$, and *D* is the total number of days. Given the notation above, the *p*-th percentile speed, denoted as $v^p(i,t)$, can be defined as follows:

$$P(v(i,t) \le v^p(i,t)) \ge p, \forall i = 1,\cdots,N, t = 1,\cdots,T\ . \tag{1}$$

Here *P* represents the *probability* and $v(i,t)$ the *random* speed at location *i* at time *t*. Further, since we have in total *D* days, $v^p(i,t)$ can be computed as follows:

$$\begin{aligned} &v^p(i,t) = \hat{v}_k(i,t) \text{ such that} \\ &k = [p \cdot D] + 1 \end{aligned} \tag{2}$$

Here $\{\hat{v}_d(i,t) \mid d = 1,\cdots,D\}$ is a non-decreasing re-ordering of the list of multiple day speeds $\{v_d(i,t) \mid d = 1,\cdots,D\}$. Also, $[a]$ denotes the integral part of a real value *a*.

From Equation (1), if the *p*-th percentile speed at detector *i* at time *t* is 35 MPH, the probability of speed at this particular location at time *t* lower than 35 MPH is at least *p**100%. In other words, if speed lower than 35MPH is considered as a bottleneck, it implies that for over *p**100%, this location will be a bottleneck. Therefore, percentile speeds can be used to describe the probability of a location being a bottleneck, which can not be modeled by other means such as average speeds. In addition, the percentile-based method provides more flexibility for bottleneck identification and calibration. Since the percentile is the probability of having a bottleneck at the given location and time, the percentile-based method allows one to consider bottlenecks either aggressively or conservatively. For example, an aggressive approach may use a lower percentile (e.g., 15%) which will result in more bottlenecks; a conservative approach may use a higher percentile resulting in fewer bottlenecks. The decision may depend upon factors like resource limitations, etc.; but in any case, both aggressive and conservative bottleneck analysis results can be presented to decision makers to make more informed decisions.

2.3 Speed Contour Maps

Based on the aforementioned method, “representative” speeds can be obtained and then used to construct a percentile speed based SCM for the studied portion of freeway. To demonstrate the methods for bottleneck analysis, we use a small example in this section. We collected observed data for a small segment of freeway and drew the following SCMs:

(1) SCM based on average speeds;
(2) SCMs from single days with and without incidents; and
(3) 15-th, 50-th, and 85-th percentile SCMs

These contours are shown in Figure 1(a) – 1(f). The segment of freeway contains nine detectors and the direction of travel is from Detector 1 to Detector 9. The value in the parenthesis by each detector in the figures indicates its postmile. Data were collected from 7:00 AM to 9:30 AM for 20 days and one bottleneck can be observed. Here we assume speed is constant from a detector to its nearest downstream detector at a given time instant. First of all, in Figure 1(b), the locations and starting and duration times of two incidents are also depicted. From Figure 1(b) and 1(c), we can see that due to possible incidents or day to day traffic variations, SCMs from single day data could vary significantly. Thus for heavily congested corridors, a “typical” day may not be easily identified; or even if it can, the data may not be reliable. From Figure 1(d) – 1(f), we can clearly see that both the spatial extent (queue length) and time duration of the bottleneck shrinks as percentile increases. Also note that the SCM based on average speeds, in this case, is similar to the 50-th percentile SCM, but they are not exactly the same. For example, the bottleneck duration is longer in the 50-th percentile SCM.

The 50-th percentile SCM in Figure 1(e) will be used to represent the typical traffic condition of the studied freeway section. Based on visual assessment, we can see that there is one major bottleneck between postmile 24.84 and 28.88. The bottleneck starts at Detector 8 at about 7:40 AM. The congestion gradually extends to upstream of Detector 8. As indicated in Figure 1(e), at 8:30 AM, the queue length at Detector 8 is about 28.65-24.84=3.81 miles and the time duration (until congestion clears) is about 30 minutes.

From Figure 1, since an SCM is indexed by i and t, it can be represented as an N by T matrix. Denote the matrix as S, and $S(i, t)$ is the speed of sensor i at time t, $\forall i = 1,2,\cdots,N$, $\forall t = 1,2,\cdots,T$. Such a matrix representation of SCMs makes the bottleneck identification and calibration easily to conduct, which will become evident in later sections.

2.4 Automatic Bottleneck Identification

As aforementioned, we assume traffic conditions, e.g., speeds, are constant between two consecutive detectors at a particular time. However, if two consecutive detectors are too far away from each other, the above assumption does not hold any more. Therefore, the bottleneck analysis methods proposed in this paper should only be applied to the Freeway Segment with Continuous Detection (FSCD). An FSCD is defined as a portion of freeway in which the maximum distance between any two consecutive detectors is less than some threshold. In this study, we use three (3) miles as the threshold, as suggested in Chen et al. (*5*). For different FSCDs, the bottleneck analysis (i.e., identification and calibration) should be conducted separately.

The most straightforward bottleneck identification method is through visual identification as discussed in Section 2.3. However, this relies heavily on manual work which may not provide very accurate and quantitative information of bottleneck information. Thus certain automatic bottleneck identification methods are needed. Chen et al. (*5*) developed such an automatic method to systematically identify freeway bottlenecks using 5-minute PeMS data. The method is based on absolute speeds of a detector and speed drops. It can automatically calculate bottleneck spatial extent and time duration. The algorithm has been implemented in PeMS.

In this paper, we propose a simplified method based on the so-called Binary SCM (BSCM). To construct a BSCM, we first set a threshold speed, e.g., 35MPH. Then speeds in the original SCM are converted into either 0 or 1 depending on whether the speed is higher than (or equal to) 35MPH or lower. For example, the BSCM of the SCM in Figure 1(e) is given in Figure 2 below. The matrix corresponding to a BSCM is denoted as *BS*. Therefore, we have either $BS(i, t) = 0$ or $BS(i, t) = 1$. Clearly, this matrix can be easily obtained from a BSCM, e.g., the one in Figure 2.

Given a BSCM, bottlenecks can be identified as the areas marked by 1's. Sometimes, there may be "holes" (0's) within a bottleneck area. In this case, we set these 0's to 1's if at a given location an isolated 0 is enclosed by five continuous data points and the other four are 1's. Here an "isolated" 0 means a "zero" with its two neighbors in the time space being 1's. The above idea can be easily computerized by manipulating the matrix (denoted as *BS*) of a BSCM. The algorithm is summarized as follows:

BSCM Bottleneck Identification Algorithm

Step 1. Removing Isolated Zeros

```
For i=1 to N
    For t = 1 to T
        If BS(i,t) == 0
          Set BS(i,t) to 1 if there is a time instant t' such that t' < t and t'+4 > t and
          BS(i,t")=1, for all t'<= t" <= t'+4 and t" ≠t.
        End
    End
End
```

Step 2. Bottleneck Identification

```
For i=N to 1
    For t = 1 to T
        If BS(i,t) == 1
           1) Trigger location i at time t as a bottleneck
           2) Find the farthest upstream detector j such that all detectors between i and j
              (including j) have speed 1 at t. Then the queue length of the bottleneck at i
              is $(x_j-x_i)$, i.e. the postmile difference of detector i and j.
           3) Find the maximum t_n such that between t and t_n (including t_n), all the
              speeds at detector i are 1. Then the time duration of the bottleneck at i
              is (t_n-t)*Δ where Δ is the length of each time interval (e.g. 5 minutes).
        End
```

```
        End
    End
```

Hence, the queue length and time duration of the bottleneck can be easily obtained by the automatic method. For example, the queue length and duration of the bottleneck at Detector 8 at 8:30 AM are indicated in Figure 2. Compared with Figure 1(e), we can see that the same results are obtained by using BSCM. Therefore, BSCM simplifies Chen's original method and is easy to conduct. More importantly, it is computationally more efficient for bottleneck calibrations as will be discussed in Section 3.2.

3. Bottleneck Calibration

3.1 Current Practice

Corridor management planning needs to evaluate different strategies in a microscopic simulation model in order to obtain more accurate estimation of the benefits. Microscopic traffic simulation is a software tool for modeling traffic system, including roadways, drivers, and vehicles. It emulates the traffic system in such a detail that the state of vehicles and traffic control devices are continuously (or discretely) updated every a small time step (usually, smaller than 0.5 second). In order for micro-simulation models to produce meaningful results, nevertheless, calibration is a critical step which matches model output with observed data in the real world. The traditional process of simulation model calibration heavily relies on the engineering judgment, i.e., to adjust the model parameters (usually demands and network) until reasonable (quantitatively and qualitatively) correspondences between field data and simulated model results are achieved (*9*).

Many calibration studies use flow data for model calibration and travel time data for model validation (*10*, *11*). FHWA's micro-simulation modeling guideline summarizes the model calibration to be a three step process, including capacity calibration, route choice calibration, and system performance calibration (*3*). System performance calibration is a step comparing the overall performance of the model with observed travel time, speed, and delay. As shown in Table 1, the calibration targets, developed by Wisconsin Department of Transportation, are the minimum performance requirements recommended by the guideline. Note that the guideline only provided calibration targets for flow and travel time data, while speed and bottleneck calibrations were all based on visual audits. In practice, SCMs constructed using speed data have been used for bottleneck calibrations of several freeway corridor networks in California (*4*, *10*, *12*). In a calibration study by Gomes et al (*6*), three speed contours, corresponding to a heavy, a typical, and a light day of traffic, were used to identify real-world bottlenecks. The calibration was conducted to match bottlenecks' start times, queue lengths, and time durations. However, the study did not match flow data because of the difficulty in determining what flow data to be used due to the large variation of traffic flow. In addition, no quantitative measures were developed.

The calibration of bottlenecks is more critical for corridor level analyses since bottlenecks can significantly impact the performance of an entire corridor. As a result, we argue that simulation model calibration needs to consider both flow and bottlenecks. Ideally, one needs to match the number, locations, shapes, areas, and actual speeds of bottlenecks generated by micro-simulation against those from the real world observed data. In this paper, we propose a three step process for bottleneck calibration, starting from rough matching to detailed calibration. Based on how “good” the model needs to be calibrated, these three steps can be used as three levels of calibration targets. The proposed method thus complements and enhances current FHWA guideline on bottleneck calibration and further provides flexibilities for simulation model development and calibrations.

3.2 Visual assessment

The first step of bottleneck calibration is to visually assess SCMs created by both simulated and observed data to make sure the number and locations of bottlenecks can roughly match. No quantitative criteria can be easily defined for this step since it highly depends on experience and engineering judgment. However, the visual assessment step is very important since it sets up the appropriate initial SCMs for the later two steps to calibrate bottlenecks in a more concrete way. To demonstrate the methods for bottleneck calibrations, Figures 3(a) and 3(b) depict, respectively, the SCM and BSCM generated from simulation for the example in Figure 1. There are two isolated zeros in Figure 3(b) which should be replaced by 1’s, resulting in the refined BSCM in Figure 3(c).

Through visual assessment, one can see that either the SCMs or BSCMs from observed and simulated data are quite close to each other. Here we use the 50-th percentile speed contour plots in Figure 1(e) and Figure 2 to represent observed data. Usually one may claim at this point that the bottleneck calibration is satisfied according to visual assessment. In the next two sections, nevertheless, we will develop methods to further conduct more rigorous bottleneck calibrations based on bottleneck areas and detailed speeds.

3.3 Match Bottleneck Area

After the first step, two SCMs (or BSCMs) will be generated, one from observed data and the other from simulation. Their SCM matrices are denoted as S_s and S_r for simulation and observation, respectively, while BSCM matrices are represented as BS_s and BS_r.

The area matching of bottlenecks can be conducted using the two BSCM matrices. In particular, the following measure is defined to indicate how well the bottleneck areas are matched between simulated and observed data:

$$C_1 = \frac{2\sum_{i=1}^{N}\{(\sum_{t=1}^{T}[BS_s(i,t)\wedge BS_r(i,t)])\cdot|x_{i^+}-x_i|\}}{\sum_{i=1}^{N}\{(\sum_{t=1}^{T}[BS_s(i,t)+BS_r(i,t)])\cdot|x_{i^+}-x_i|\}}, \tag{3}$$

where i^+ is the nearest downstream detector of i and $|a|$ denotes the absolute value of a. Also in Equation (3), "$\wedge$" denotes the "and" operator and we have $0 \wedge 0 = 0$, $0 \wedge 1 = 0$, $1 \wedge 0 = 0$, and $1 \wedge 1 = 1$.

From Equation (3), C_1 is the proportion of the overlapping area of simulated and observed BSCMs with respect to the average of the two. The definition considers the spatial extent (i.e., the spacing between detectors) by incorporating $|x_{i^+}-x_i|$, the distance of two consecutive detectors. Clearly, C_1 ranges from 0 to 1. A larger C_1 value means a better match between the simulated and observed bottlenecks. In particular, "1" means the areas of the two are perfectly matched.

For the observed and simulated data in Figure 1 and Figure 3, Figure 3(d) first illustrates the overlapping area of the two BSCMS in Figure 2 and Figure 3(c).

One can then calculate $C_1 = 90.5\%$ from Equation (3) based on the postmile information shown in Figure 1.

The calibration criteria for bottleneck area matching can be set as

$$C_1 \geq \delta_1 . \tag{4}$$

Here δ_1 is the threshold.

3.4 Detailed Bottleneck Calibration

If the second step for matching bottleneck areas is satisfied, the last step will be the detailed speed calibration. This step is conducted on SCM areas that are either in simulation or observed bottlenecks. Therefore, it is based on the original SCMs from simulated and observed data. In particular, we define another measure, denoted as C_2, as the objective function for the calibration in this step:

$$C_2 = 1 - \frac{2\sum_{i=1}^{N}\{(\sum_{t=1}^{T}[BS_s(i,t)\vee BS_r(i,t)]\cdot|S_s(i,t)-S_r(i,t)|)\cdot|x_{i^+}-x_i|\}}{\sum_{i=1}^{N}\{(\sum_{t=1}^{T}[BS_s(i,t)\vee BS_r(i,t)]\cdot[S_s(i,t)+S_r(i,t)])\cdot|x_{i^+}-x_i|\}}. \tag{5}$$

Here "$\vee$" is the "or" operator and we have $0 \vee 0 = 0$, $0 \vee 1 = 1$, $1 \vee 0 = 1$, and $1 \vee 1 = 1$. Note that $S_s(i,t)$ and $S_r(i,t)$ here are the actual speeds from simulated and observed data. Further, the calibration is based on the *union* of bottlenecks from simulated and observed SCMs since bottlenecks are the most interesting to simulation calibrations. Figure 3(e) depicts the union of bottlenecks for the example discussed above. Obviously, C_2 ranges from 0 to 1 as well with a larger value representing a better match. In particular, the bottlenecks in the two SCMs will exactly match, in terms of both areas and actual speeds, if C_2 is equal to 1.

For the above example, one can obtain C_2 = 64.2% by considering the actual speeds of SCMs in Figure 1(e) and Figure 3(a).

Similarly as for area matching, a calibration criterion can be set up by introducing another threshold δ_2 such that:

$$C_2 \geq \delta_2 . \tag{6}$$

In general, the calibration of both the second and third steps is to adjust model parameters so that their corresponding measures can be maximized to the extent possible. Many methodologies in this regard have been proposed in the literature (*6*, *9*, *10*, *13*).

4. A Real World Example

In this section, we provide a real world example using the northbound I-880 corridor in the San Francisco Bay Area in order to demonstrate the bottleneck analysis methods proposed in this paper. Figure 4 is a map of the I-880 corridor with the two “stars” indicating the starting and ending points of the network. The I-880 corridor is currently being studied by a team of researchers including the authors, researchers from the University of California at Irvine, and System Metrics Group (a private consulting firm). The purpose is to develop corridor management planning strategies for Caltrans via applying detailed micro-simulation techniques (Paramics was used). Results from this study are used to support the real world example in this section. The detection system of I-880 is a double-loop system and thus speed data provided by PeMS are measured speeds. Also, its detector spacing is sufficient since most of its freeway segments have detection coverage at intervals of ½ mile or less. Twenty days of northbound I-880 data were collected from January to February of 2006 for only Tuesdays, Wednesdays, and Thursdays. The simulation was conducted for AM peak period from 6:30 to 9:30. The simulation data used in this section is an interim result, not necessarily the final results from the simulation model.

The I-880 simulation model was calibrated against a set of flow data, including data at 42 mainline locations and 93 on-ramp and off-ramp locations, and a set of travel time data collected using floating car runs. As shown in Table 2a, the GEH of most mainline and ramp links are less than 5, which satisfies FHWA’s recommended flow calibration criteria (as illustrated in Table 1). As shown in Table 2b, the northbound I-880 has a total of seven sections. Among them, simulated travel times of six sections satisfy the FHWA guideline, equivalent to 86% of all sections. Regarding the total travel time for the whole studied northbound, its percent error is -7.0%. In addition, as shown in Figures 5(a) and 6(a), two bottlenecks can be identified in both simulated and observed data and their locations are roughly matched with each other. Hence, one may claim that the simulation model has been calibrated satisfactorily according to the FHWA guideline.

We next show the bottleneck identification and calibration results for the studied corridor. Firstly, the observed 50-th percentile SCM and BSCM are what we use for the analysis, as shown in Figure 5(a) and 5(b), respectively. The simulation SCM and BSCM are depicted in Figure 6(a) and 6(b). We can first observe that the bottleneck identified using the BSCM method is appropriate to represent the actual bottlenecks in both observed and simulated data. Furthermore, using Equations (3) and (5), the value of C_1 and C_2 can be calculated as C_1= 24.2%, C_2 =42.5%.

Clearly, although the calibration based on flow and travel time is satisfied according to current practice and guidelines, the bottleneck calibration result is rather unsatisfactory. Our proposed two measures, however, can capture quantitatively how well the bottlenecks are matched with each other. Therefore, the proposed bottleneck calibration method complements and improves existing simulation guidelines. The proposed method may be included into future simulation calibration guidelines for more rigorous bottleneck calibrations.

5. Conclusions

This paper proposed approaches for bottleneck identification and calibration in corridor management planning. The approaches were based on percentile speeds by using data from multiple days. It turned out that this is more appropriate for urban congested freeways than using single day data. The bottleneck identification was conducted on speed contour maps either manually or automatically. Especially, an automatic identification algorithm was developed by manipulating the matrix representing binary speed contour maps. The algorithm for bottleneck calibration was proposed as a three-step process, which could be regarded as three levels of calibration targets. In the first step, visual assessment was performed to make sure a general match of number of bottlenecks and locations between simulated and observed data. This step is actually consistent with current FHWA simulation calibration guideline. The second step was to match areas of bottlenecks based on a newly developed measure using binary speed contour maps. Finally, an objective function was defined in the third step to further match detailed speeds of bottlenecks. To demonstrate the proposed approaches, a real world example was provided using the I-880 corridor network in the Bay Area. The result showed that the proposed bottleneck identification method can generate adequate bottleneck plots. Furthermore, the measures developed can properly capture how bottlenecks are matched with each other. This illustrated that the proposed bottleneck calibration method complements and further improves current state of practice for simulation calibration.

Although presented using speed data, the methods proposed in this paper may also be applied to flow and occupancy data since both of them have been used for bottleneck identification purposes. This is particularly useful for areas where speed data is not available (e.g., only single loops were deployed and thus speeds are not directly measurable). The authors are currently working on using flow and occupancy data to identify and calibrate corridor bottlenecks. On the other hand, 5-min data were used in this paper, which may not be available for many areas in the U.S. Although the methods developed in this paper do not have restrictions on the temporal resolution of the data, the bottleneck analysis results will be impacted significantly by the data resolution. It is easy to observe from the proposed methods that the accuracy of the analysis (e.g., locations and durations of bottlenecks) is directly determined by the resolution of the given data. In this sense, one needs to balance the data collection efforts and quality of the analysis. The authors will further pursue research in this direction to provide recommendations on the appropriate temporal resolution of input data.

Furthermore, the proposed bottleneck identification and calibration methods need to be further tested in more studies. In particular, practical approaches need to be developed to address how to adequately adjust model parameters to facilitate the three-step bottleneck calibration procedure. This will help to incorporate more rigorous bottleneck calibrations in future simulation development practice.

Acknowledgement

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Figure 2 An Illustration of BSCM

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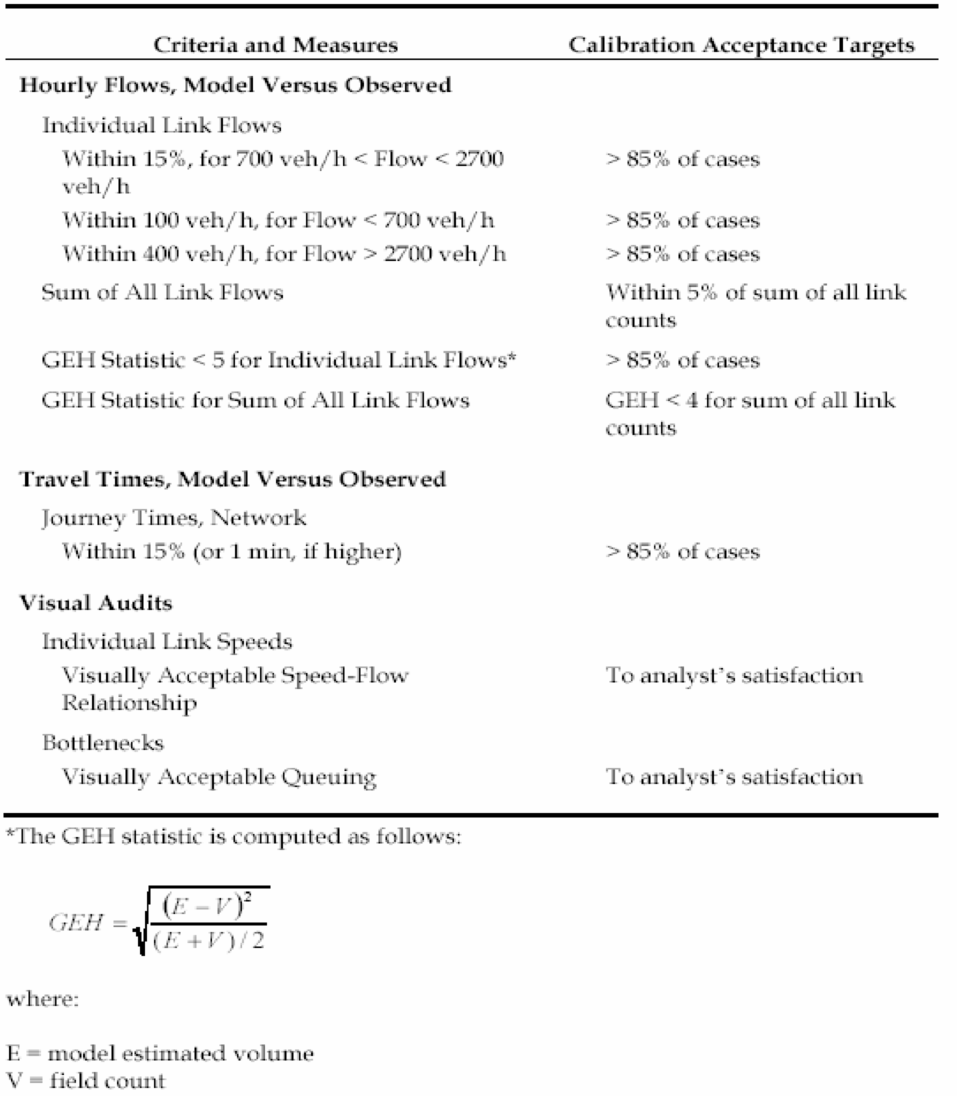
Figure 4 The Studied I-880 Corridor Network

Figure 5 Observed 50-th Percentile Speed Contour Map (a) SCM, (b) BSCM

Figure 6 Simulated 50-th Percentile Speed Contour Map (a) SCM, (b) BSCM

Table 1 Calibration Targets Suggested by FHWA Guideline



Criteria and Measures	Calibration Acceptance Targets
Hourly Flows, Model Versus Observed	
Individual Link Flows	
Within 15%, for 700 veh/h < Flow < 2700 veh/h	> 85% of cases
Within 100 veh/h, for Flow < 700 veh/h	> 85% of cases
Within 400 veh/h, for Flow > 2700 veh/h	> 85% of cases
Sum of All Link Flows	Within 5% of sum of all link counts
GEH Statistic < 5 for Individual Link Flows*	> 85% of cases
GEH Statistic for Sum of All Link Flows	GEH < 4 for sum of all link counts
Travel Times, Model Versus Observed	
Journey Times, Network	
Within 15% (or 1 min, if higher)	> 85% of cases
Visual Audits	
Individual Link Speeds	
Visually Acceptable Speed-Flow Relationship	To analyst's satisfaction
Bottlenecks	
Visually Acceptable Queuing	To analyst's satisfaction

*The GEH statistic is computed as follows:

$$GEH = \sqrt{\frac{(E-V)^2}{(E+V)/2}}$$

where:

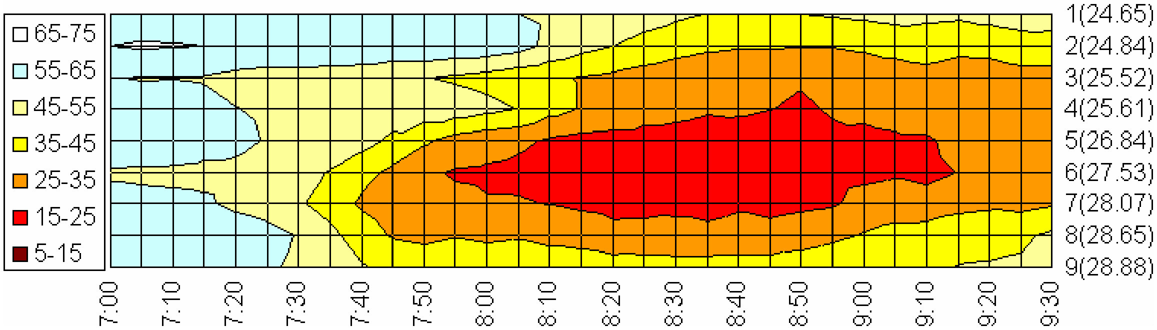
E = model estimated volume
V = field count

Table 2a Northbound Flow Calibration Results

	Interval 1 (7:00-8:00 am)		Interval 2 (8:00-9:00 am)	
	Mainline	Ramp	Mainline	Ramp
GEH: 0-5	95%	85%	86%	85%
GEH: 5-10	5%	15%	14%	15%
Satisfies Guideline?	95%	85%	86%	85%

Table 2b Northbound Travel Time Calibration Results

Start	End	Observed (Seconds)	Simulated (Seconds)	Difference (Seconds)	Diff(%)	Satisfies guideline?
N. start	Automall	381	424.8	43.8	11.50%	TRUE
Automall	SR-84	307	340.5	33.5	10.91%	TRUE
SR-84	SR-92	676	528.5	-147.5	-21.82%	FALSE
SR-92	I-238	234	187.2	-46.8	-20.00%	TRUE
I-238	98th St	387	353.7	-33.3	-8.60%	TRUE
98th St	29th St	322	266.6	-55.4	-17.20%	TRUE
29th St	N. end	327	349.5	22.5	6.88%	TRUE
N. start	N. end	2634	2450.8	-183.2	-6.96%	TRUE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3(25.52)
4(25.61)
5(26.84)
6(27.53)
7(28.07)
8(28.65)
9(28.88)
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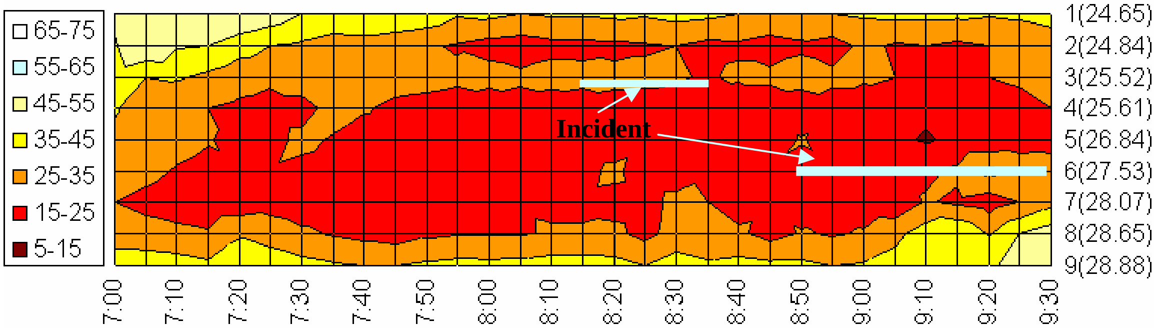
1(a)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Incident
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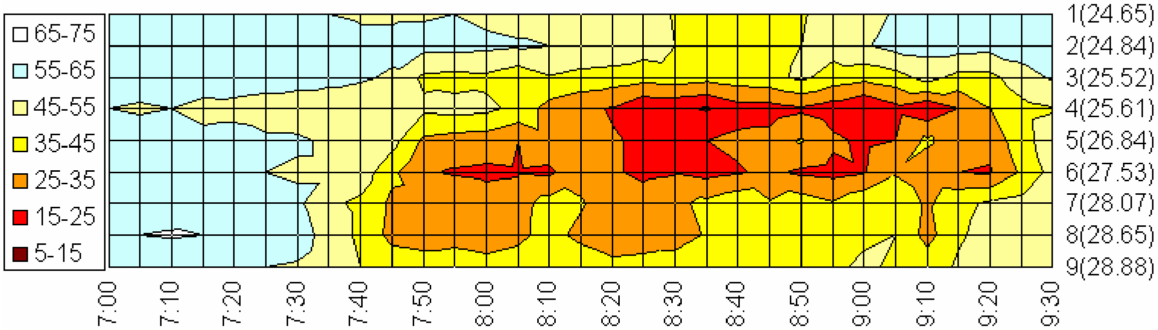
(1b)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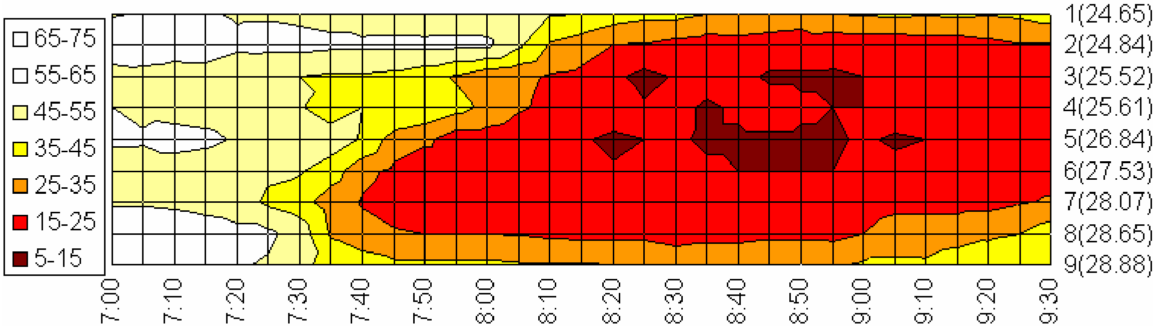
1(c)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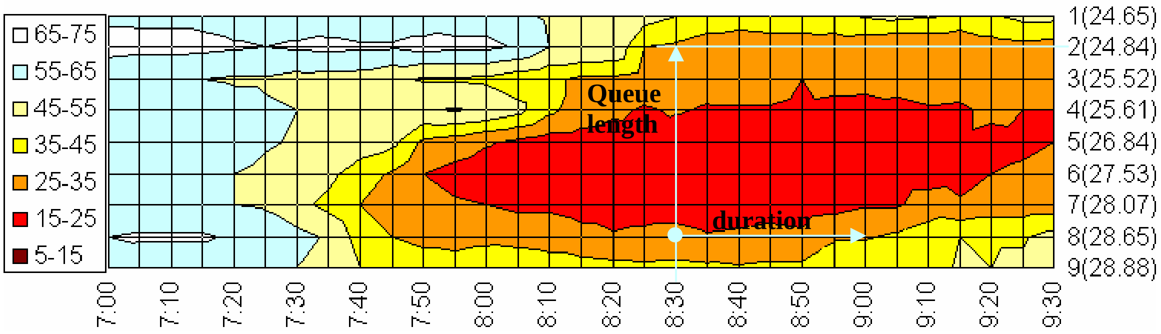
1(d)



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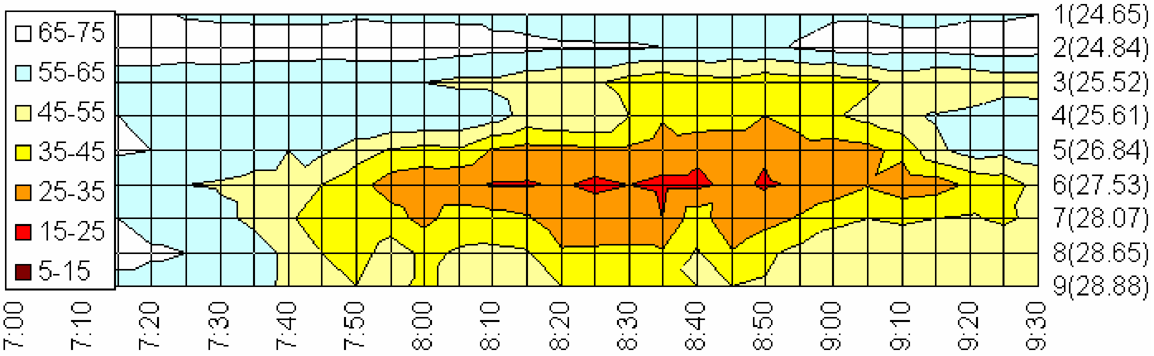

1(f)

Figure 1 Illustration of SCM from Observed Data: (a) Average Speed, (b) Single Day – With Incident, (c) Single Day – Without Incident, (d) 15-th Percentile Speed, (e) 50-th Percentile Speed, (f) 85-th Percentile Speed

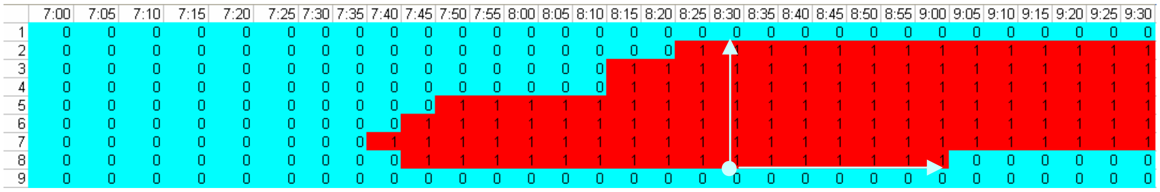

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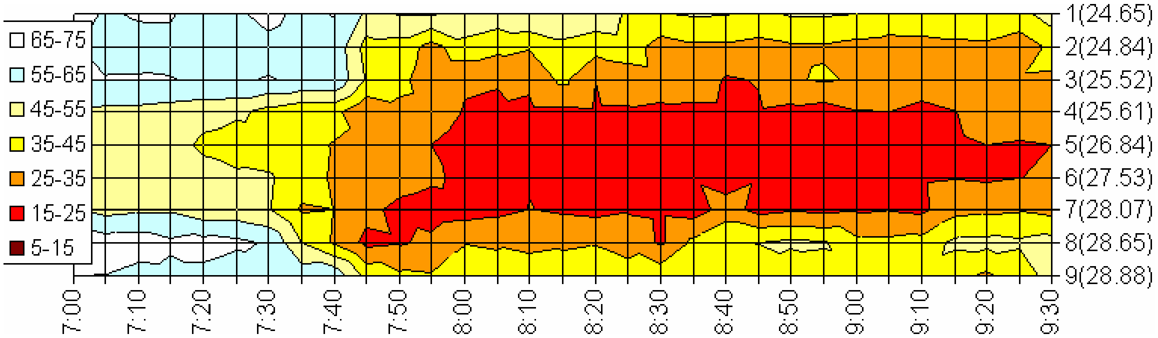
Figure 2 An Illustration of BSCM



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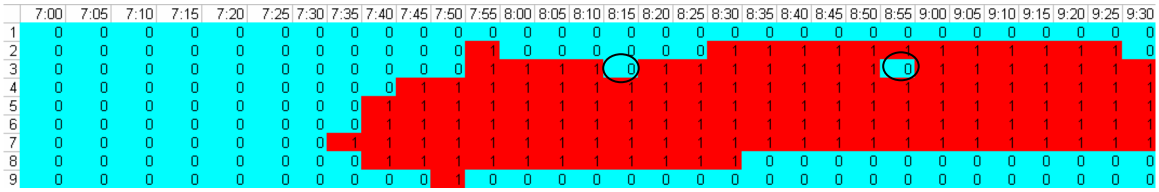

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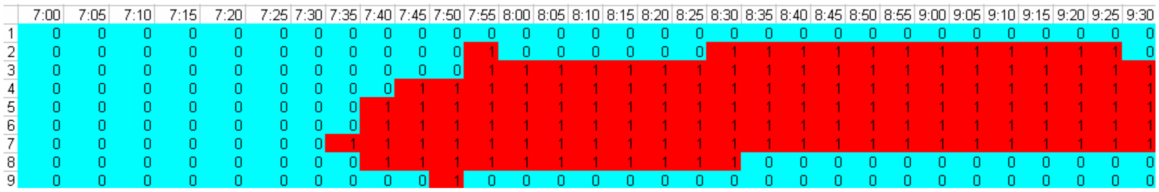

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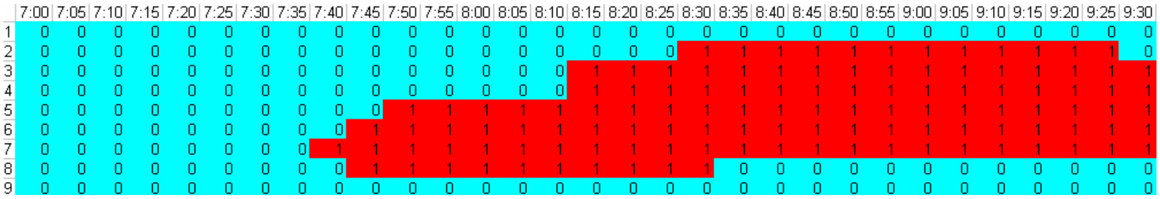

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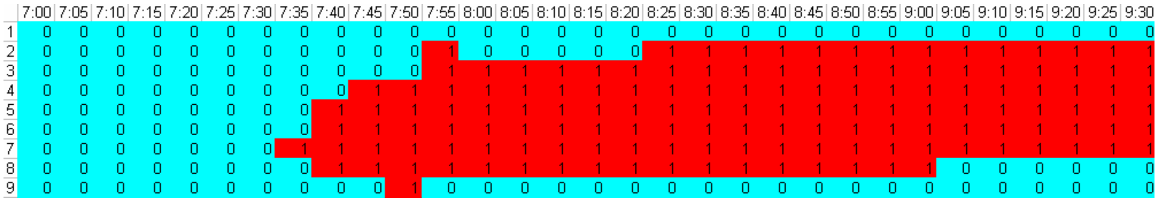

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3(e)

Figure 3 Speed Contour Maps by Simulation Data (a) SCM, (b) BSCM, (c) Refined BSCM (after removing isolated zeros), (d) Overlapping Area of Simulated and Observed BSCMs, (e) Union Area of Simulated and Observed BSCMs

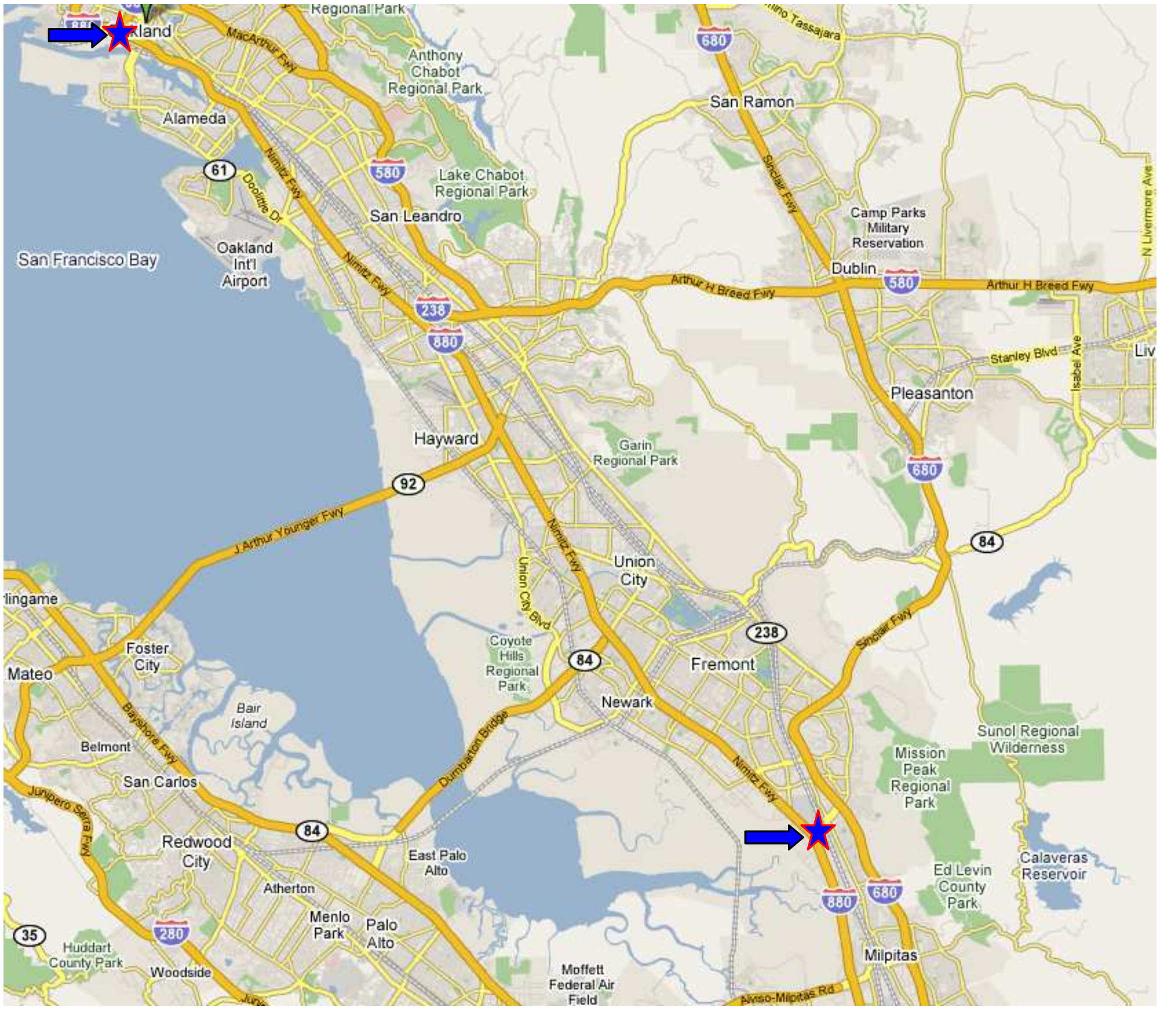


Figure 4 The Studied I-880 Corridor Network (Source: Google Map)

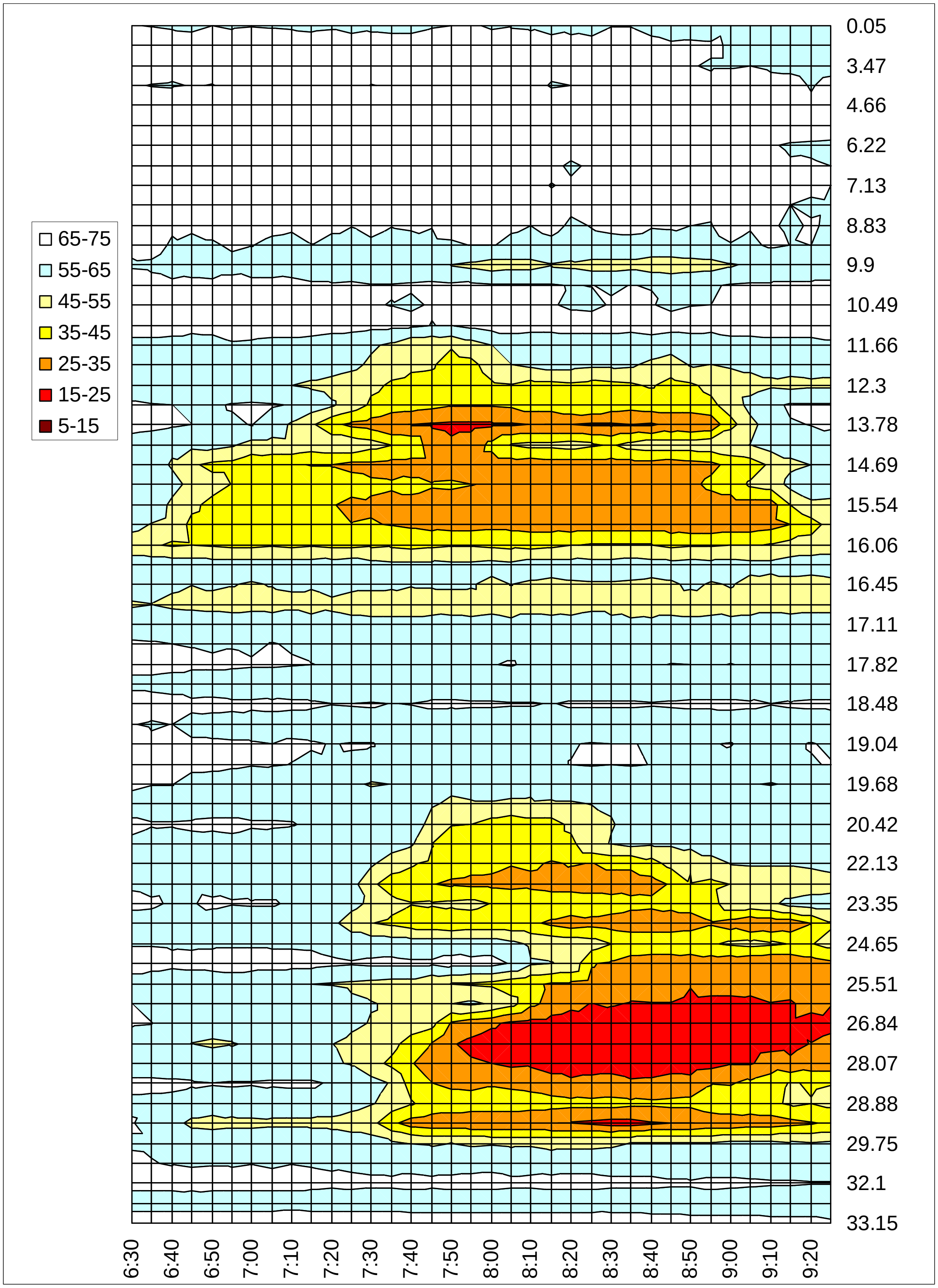
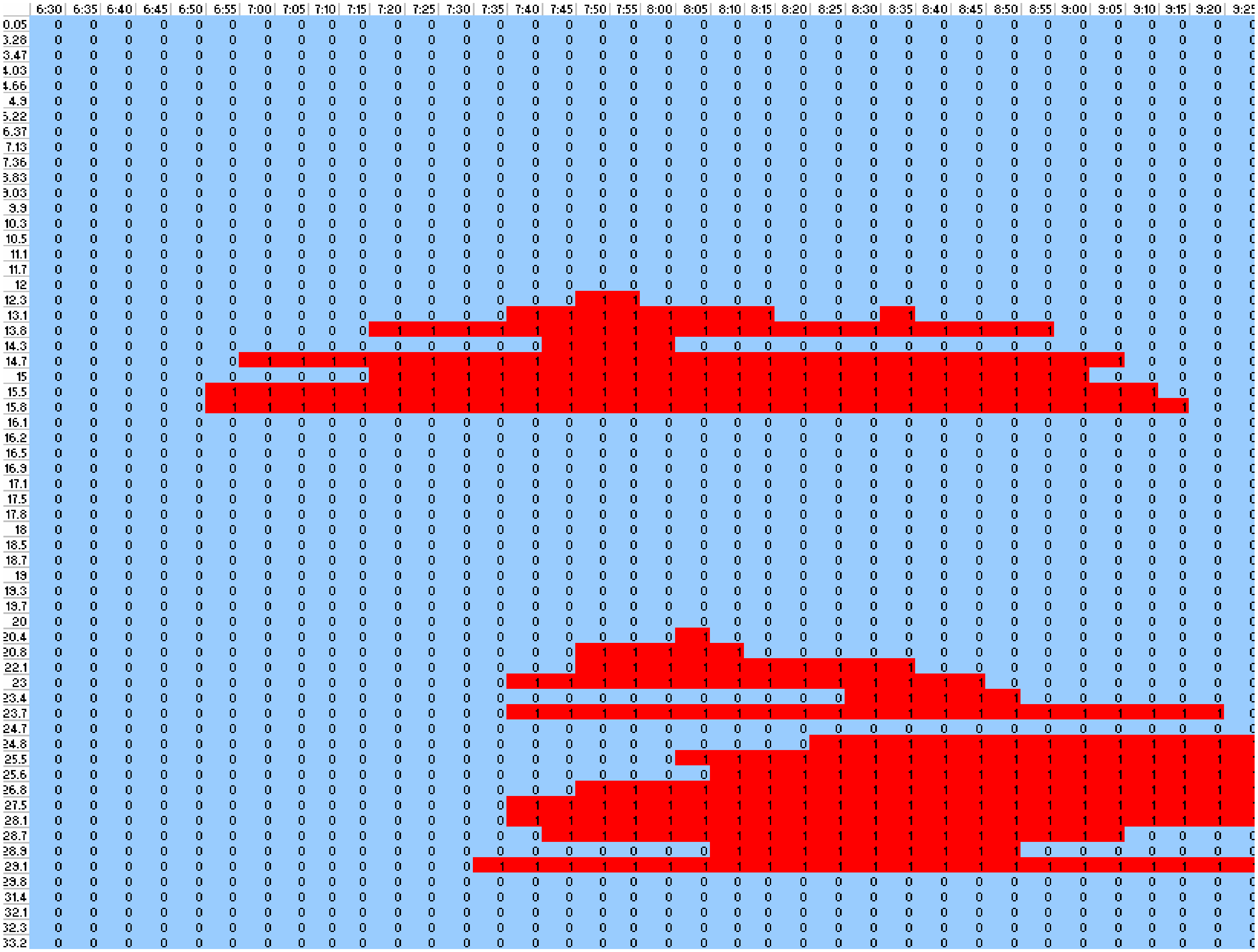


Figure 5(a) Observed 50-th Percentile SCM



	6:30	6:35	6:40	6:45	6:50	6:55	7:00	7:05	7:10	7:15	7:20	7:25	7:30	7:35	7:40	7:45	7:50	7:55	8:00	8:05	8:10	8:15	8:20	8:25	8:30	8:35	8:40	8:45	8:50	8:55	9:00	9:05	9:10	9:15	9:20	9:25
0.05	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3.28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3.47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4.03	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4.66	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5.22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6.37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7.13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7.36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8.83	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9.03	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0
13.8	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0
14.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14.7	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0
15.5	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0
15.8	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0
16.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0
23.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0
23.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
24.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1
25.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
25.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
26.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
27.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
28.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
28.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0
28.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0
29.1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
29.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
31.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
32.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
32.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
33.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 5(b) Observed 50-th Percentile BSCM

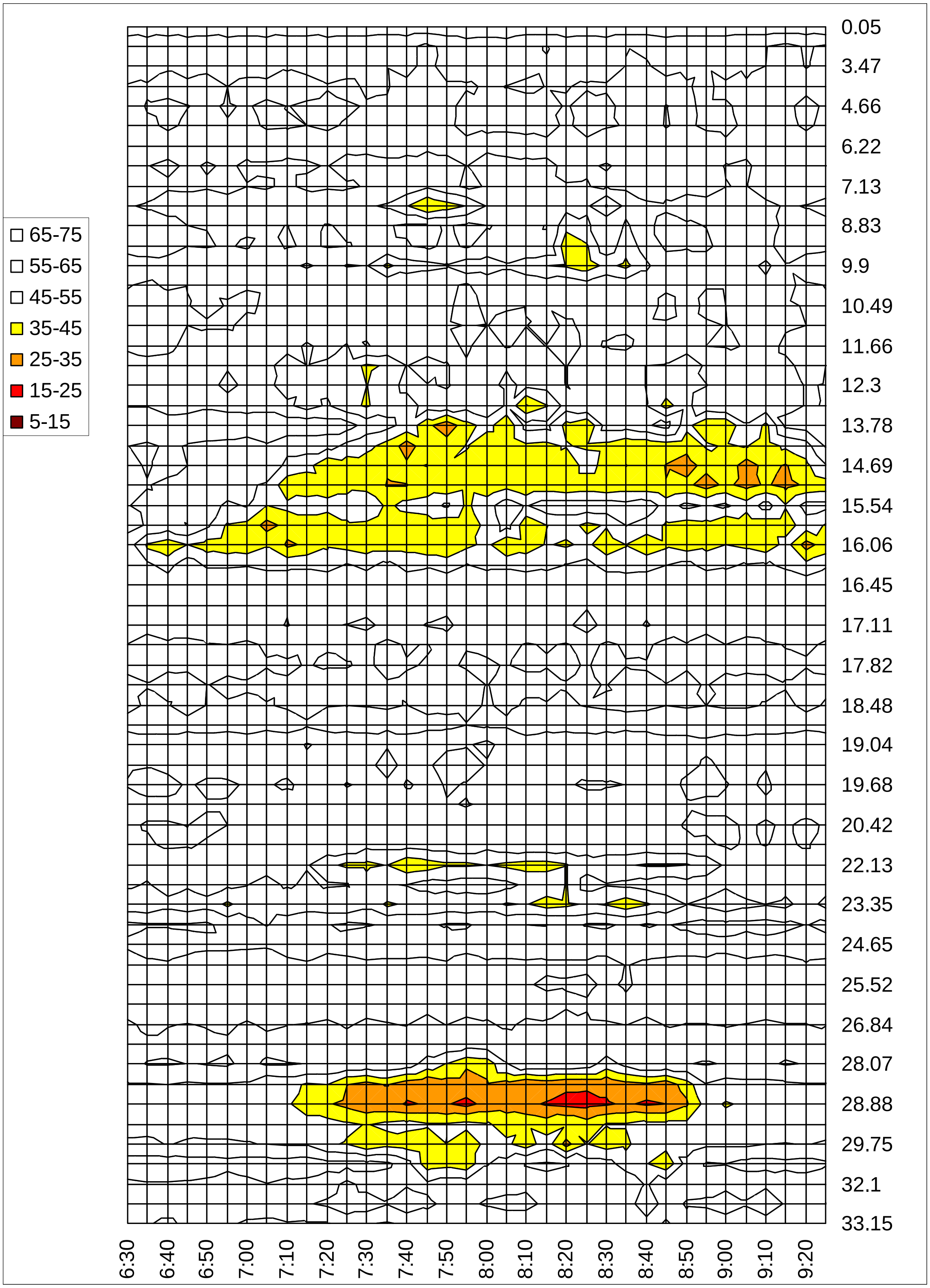
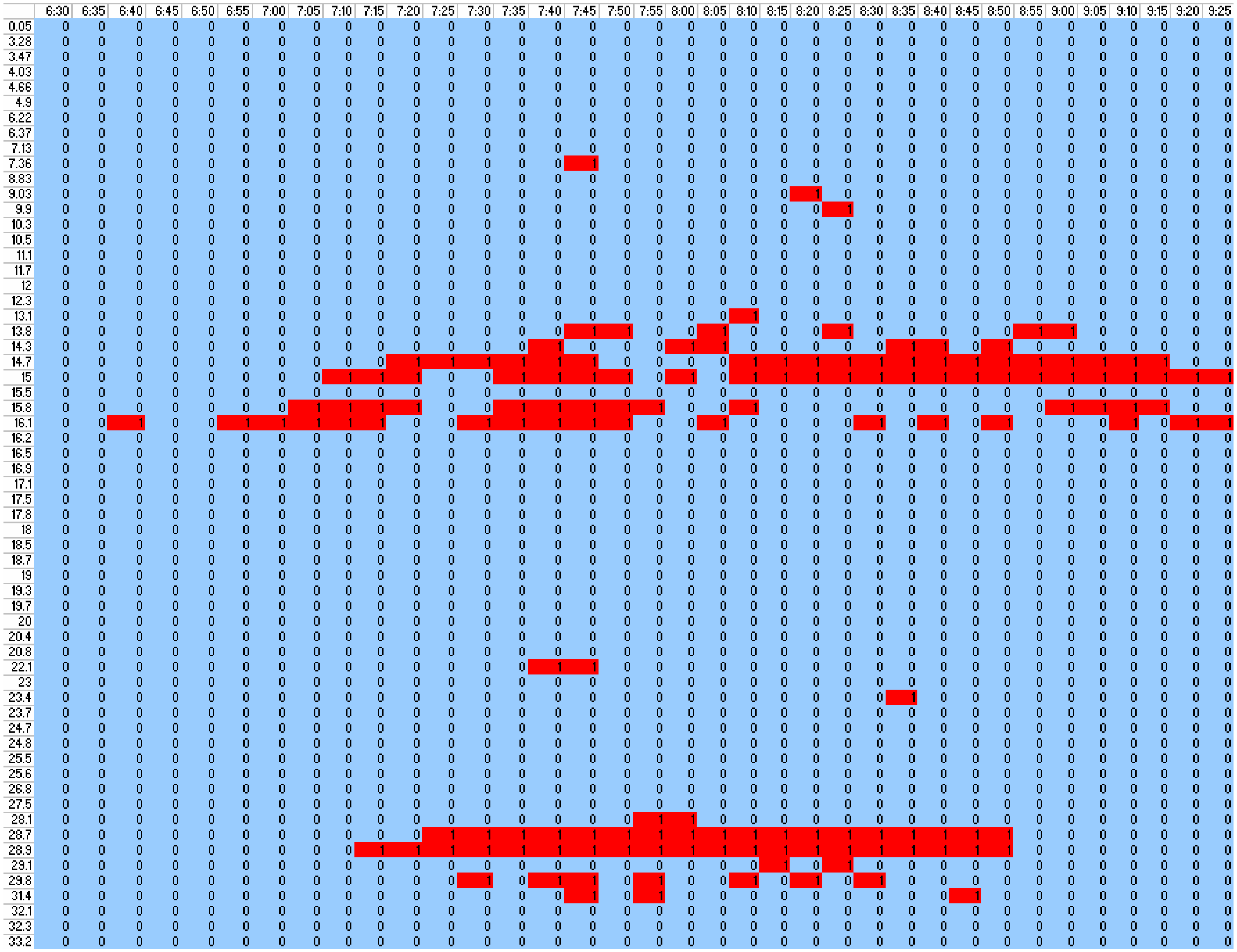


Figure 6 (a) Simulated Speed Contour Map - SCM



	6:30	6:35	6:40	6:45	6:50	6:55	7:00	7:05	7:10	7:15	7:20	7:25	7:30	7:35	7:40	7:45	7:50	7:55	8:00	8:05	8:10	8:15	8:20	8:25	8:30	8:35	8:40	8:45	8:50	8:55	9:00	9:05	9:10	9:15	9:20	9:25
0.05	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3.28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3.47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4.03	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4.66	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6.22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6.37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7.13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7.36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8.83	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9.03	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
9.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
10.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	1	0	0	0	1	0	0	0	0	0	1	1	0	0	0	0	0
14.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	1	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0
14.7	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0
15	0	0	0	0	0	0	0	0	1	1	1	0	0	1	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
15.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15.8	0	0	0	0	0	0	0	1	1	1	1	0	0	1	1	1	1	1	0	0	1	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0
16.1	0	0	1	0	0	1	1	1	1	1	0	0	1	1	1	1	1	0	0	1	0	0	0	0	1	0	1	0	1	0	0	0	1	0	1	1
16.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
23.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
26.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
27.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28.7	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0
28.9	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0
29.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0
29.8	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	0	1	0	0	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0
31.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
32.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
32.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
33.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 6(b) Simulated Speed Contour Map - BSCM