Evaluating the Performance of Network Screening Methods for Detecting High Collision Concentration Locations on Highways

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Abstract

This paper documents findings from evaluating performances of three different methods for segmenting freeway sites for the purpose of identifying high collision concentration locations: Sliding Moving Window (SMW), Peak Searching (PS) and Continuous Risk Profile (CRP). The traffic collision data from sites segmented in each method under two different roadway definitions were used to estimate excess expected average crash frequency with Empirical Bayes adjustment with respect to two different sets of Safety Performance Functions (SPFs). The estimates from each of the methods were then used to prioritize the detected sites for safety investigation and these lists were compared with previously confirmed high collision concentration locations (or hot spots). The input requirements for each of three methods were identical, yet their performance markedly varied. The findings revealed that CRP method has the lowest false positive (i.e., requiring a site for safety investigation while it is not needed) rate. The performances of SMW and PS significantly varied when different sets of SPFs were used while that of CRP was less affected.

Highlights

- We evaluated performances of three high collision concentration location methods.
- SMW and PS can converge to CRP.
- Different SPFs and segment definitions were applied to test their robustness.
- False positive rates of SMW and PS were markedly higher than that of CRP.
- The hot spot detection efficiency of CRP outperformed those of SMW and PS methods.

Keywords: *safety performance function, Continuous Risk Profile, Peak Search, Sliding Moving Window, high collision concentration location*

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1. Introduction

High collision concentration location (HCCL) detection procedure that a state department of transportation (DOT) adopts essentially dictates how DOT allocates hundreds of millions of dollars of tax payers' money in safety improvement projects. Therefore, improving the efficiency of a HCCL detection procedure has long been important topic not only to practitioner but also to researchers around the world.

Previous studies (Cheng and Washington, 2005; Elvik, 2007; Huang et al., 2009) evaluated what type of estimated statistics from a *site* shall be considered to minimize false positives (i.e., requiring a site for a safety investigation while it is not needed) and false negatives (i.e., not requiring a site for a safety investigation while it is needed) to enhance the return on state's investment on safety improvement projects. Other study (AASHTO, 2010) also evaluated pros and cons of using different types of statistics in HCCL detection procedure.

However, the effect of different network screening procedures on the performance of HCCL detection procedure has not been carefully evaluated using empirical data. To this end, this paper evaluated the performances of two commonly used network screening procedures, Sliding Moving Window (SMW) and Peak Searching (PS) methods (AASHTO, 2010), and a recently developed approach, Continuous Risk Profile (CRP) method (Chung et al, 2009, 2011), using the empirical data from California freeways under two different roadway segment definitions with two different sets of Safety Performance Functions (SPFs) in an effort to assist state agencies in improving the performance of their hot spot identification procedure.

All three methods require traffic volume, collision data, and SPF for their analysis, and they only differ in a way how they determine the endpoints of a site: SMW and PS predefine the start and end location of a roadway segment only based on roadway attributes while CRP lets the SPF and traffic collision data to define the endpoints of a site. Based on the traffic collision data from the sites segmented in each method, the excess expected average crash frequency with Empirical Bayes adjustment (AASHTO, 2010) were estimated using two different sets of SPFs: one set of SPFs is currently being used by California Department of Transportation (Caltrans) (Caltrans, 2002), and the functional form of the other set of SPFs had been developed by previous studies (AASHTO, 2010; Harwood et al., 2010; Tegge et al., 2010). Only their parameters were recalibrated using California data in this study. The excess expected average crash frequency has been considered as the potential for safety improvement (PSI) of a site and used to prioritize sites for safety investigation. The ranked sites are then compared with previously confirmed hot spots (CHS) as high collision concentration locations for the purpose of comparing the performance of SMW, PS, and CRP methods.

The description of data used to develop SPFs and the performances of two different sets of SPFs are provided in section 2. Section 3 qualitatively explains SMW, PS and CRP methods. The findings from applying two different sets of SPFs with SMW, PS and CRP methods are reported in section 4, and this paper ends with brief concluding remarks in section 5.

2. Safety Performance Function (SPF)

Safety Performance Function (SPF) is an observed mathematical relationship between explanatory variables and the collision frequency among the same type of roadway group (i.e., section of roadway that shares similar features) (Harwood et al., 2010; Tegge et al., 2010) and plays important role in detecting HCCL. In developing SPF for a roadway group, one needs to have access to: (i) explanatory variable; (ii) endpoint postmiles of different roadway groups; and (iii) traffic collision data. Issues can arise when the variance of SPF and the value of SPF itself are contaminated with bias (Chung et al 2009) due to inherent uncertainty in data used in developing SPF. Therefore, it is important to evaluate the robustness of HCCL detection procedure with respect to perturbation of SPFs. If the result of HCCL detection procedure that a state uses markedly varies with respect to a small perturbation of SPF, the state may need to allocate additional resources to improve the performance of SPF. Section 2.1 of this paper qualitatively discusses definition of roadway group, segment, and sites together with some of the inherent issues in developing SPFs. Section 2.2 discusses two different sets of SPFs used in present study and reports on their performances.

2.1 Discussion of Data for Developing SPF

2.1.1 Roadway Group, Segment and Sites

There exists more than one guideline that a state agency can utilize to categorize their roadway system into different roadway groups. Hence, different states can have identical roadway system, traffic volume and traffic collision data, but can end up categorizing their roadway groups in different ways which will lead them to developing different sets of SPFs to explain the same set of data.

According to the Highway Safety Manual (HSM) (AASHTO, 2010), a roadway segment can be defined as a portion of a facility that has a consistent roadway cross-section and its endpoints can be marked by changes in Annual Average Daily Traffic (AADT), median type and other roadway features. The HSM also discusses a number of other potential characteristics that can be used to define the endpoints of the segment within a highway rate group.

Since utilizing all the potential characteristics discussed in the HSM to define endpoints of segments will make the analysis unnecessarily complicated, the end points defined by changes in highway rate group and changes in volume were used in this report to determine the end points of a segment. The term “site” will be used to refer to sections of the roadway detected as hot spots based on the Sliding Moving Window (SMW), Peak Searching (PS), and Continuous Risk Profile (CRP) methods. In the case of SMW and PS, the end points of sites will coincide with the end points of segments. The end points of sites detected by CRP method will be independent of the end points of segments. Additional description of the *site* is provided in next section.

2.1.2 Reclassification of Roadway Group

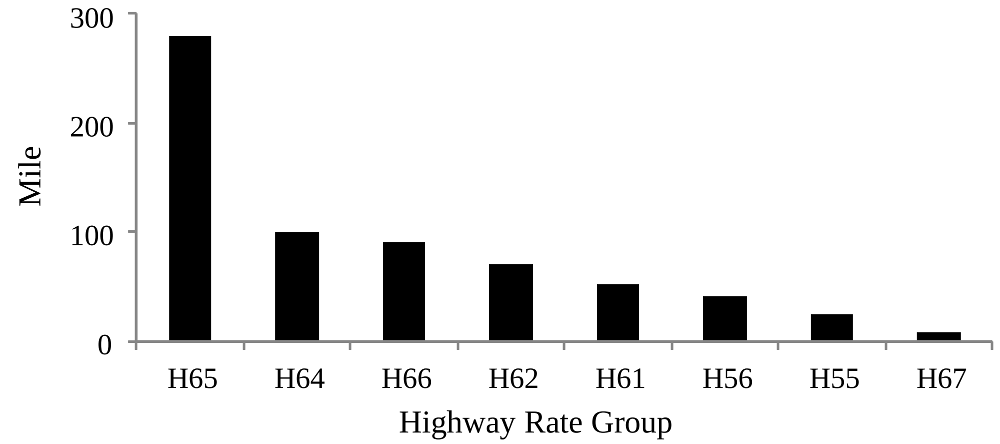
Caltrans currently classifies state-owned freeways and highways into 67 groups based on facility features (i.e., number of lane and design speed), and it has SPFs for each group

(Caltrans, 2002). The origin of Caltrans roadway classification predates 1973, and the functional form of Caltrans existing SPFs are substantially different from recently proposed SPFs by Federal Highway Administration (FHWA): the functional form of Caltrans SPF is linear or parabolic function whereas the functional form of SPF developed by FHWA is power function. Investigation of current Caltrans roadway classification revealed that several roadway groups defined in existing roadway group classification can even rarely be found. In addition, some of the existing Caltrans SPFs for existing facilities no longer explain the traffic collision data adequately; empirical evidence that supports this statement will be presented momentarily.

The number of miles that belongs to different roadway groups defined by Caltrans is shown in Fig. 1(a). Notice how the number of miles that belongs to each of Caltrans existing roadway group is disproportionate. If one were to construct a figure similar to Fig. 1(a) using data from entire California, the magnitude of the disproportionate distribution will increase even more due to the number of miles that does not belong in the Caltrans existing roadway groups.

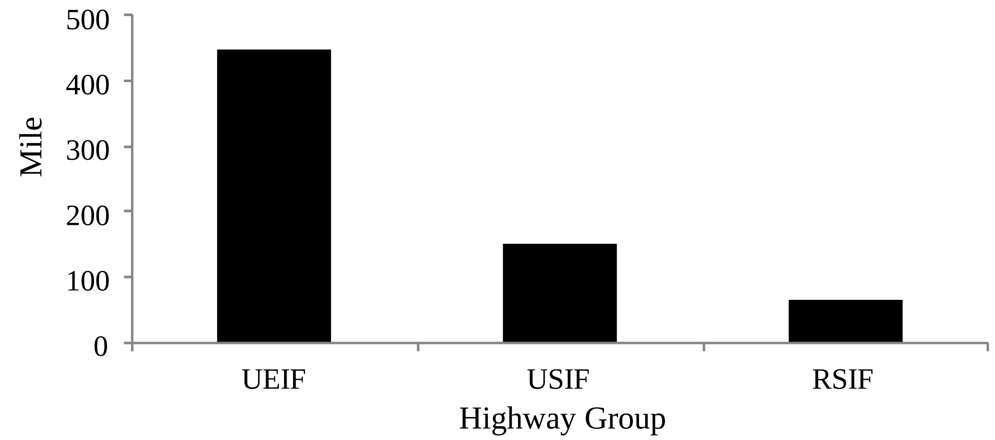
Roadway groups in Fig. 1(a) were reclassified into three groups (see Fig. 1(b)) based on the roadway description provided in Harwood et al. (2010) to have enough sample sites for each roadway group in developing SPFs. This reclassification resulted in combining two or more groups shown in Fig. 1(a) into one group. The relationship between Caltrans and the new roadway group is shown in Fig. 1.

(a)



Caltrans Roadway Classification	Description	Relationship to New Roadway Classification
H55	Rural Freeway 5-6 lanes	RSIF
H56	Rural Freeway 7 lanes or more	RSIF
H61	Suburban Freeway 5-6 lanes	USIF
H62	Suburban Freeway 7 lanes or more	UEIF
H64	Urban Freeway 5-6 lanes	USIF
H65	Urban Freeway 7-8 lanes	UEIF
H66	Urban Freeway 9-10 lanes	UEIF
H67	Urban Freeway 11 lanes or more	UEIF

(b)



New Roadway Classification	Description	Relationship to Caltrans Roadway Classification
RSIF	Rural Freeway 5 lanes or more	H55,H56
USIF	Urban or Suburban Freeway 5-6 lanes	H61,H64
UEIF	Urban or Suburban Freeway 7 lanes or more	H62,H65,H66,H67

Fig. 1. Distribution of Roadway Groups Found in the Study Site: (a) Caltrans Roadway Groups, (b) Reclassified Roadway Groups

Based on the description in Fig. 1(b), the endpoints of roadway groups were obtained from Caltrans highway database. The roadways were then further divided into segments. In present study, the endpoints of segment were defined in two different ways (see Fig. 2) to evaluate the effect of using different segment definition in generating hot spot list. It is important to note that the length of segment is always less than or equal to the length of roadway group.

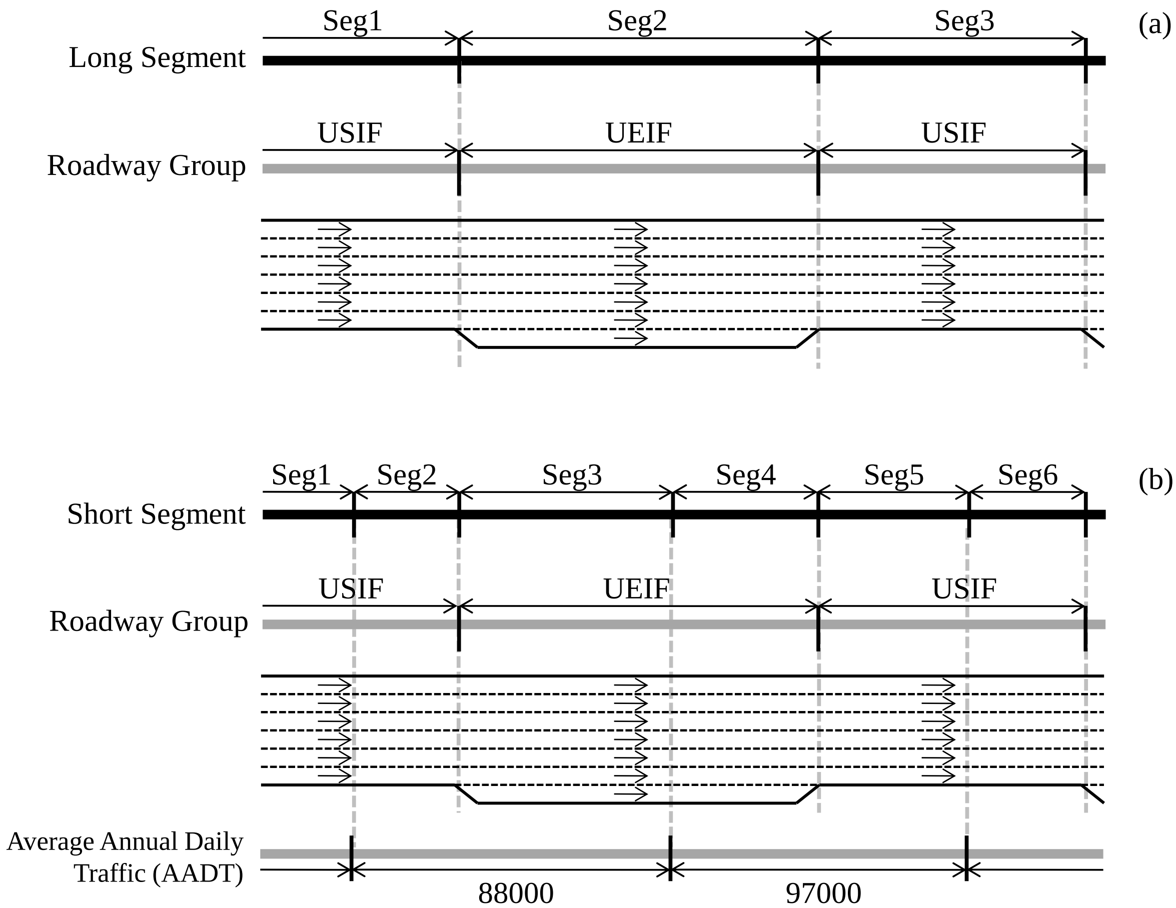


Fig. 2. Two Ways to Define Roadway Segment: (a) Long Segment, (b) Short Segment

Fig. 2(a) shows segments whose endpoints coincide with the endpoints of roadway groups defined by Caltrans. In this case, the length of segment is the same as the length of roadway group and it varied from 0.05 to 11.38 miles in present study. Traffic volume measurement locations were also used to further subdivide segments (see Fig. 2(b)). The length of segments defined in a manner illustrated in Fig. 2(b) varied from 0.04 to 3.64 miles. From here on, the segment whose size is the same as the roadway rate group will be referred as long segment (LS) and the segments whose endpoints were defined by the system illustrated in Fig. 2(b) will be referred as short segment (SS). The traffic collision data from SS were used to develop SPFs in present study.

The purpose of using two different segment definitions is to evaluate the changes in the performance of SMW, PS and CRP methods with respect to different segment lengths. Evaluating the effect of changing segment length on the performance of HCCL detection procedure is important for number of reasons. As an example, the endpoints of existing segments can change over the years due to changes in traffic volume and geometric configurations. Also as it is explained in earlier section of the paper, there is more than one guideline for defining the endpoints of segments. Depending on which guideline is adopted or changes in the facility that occur over time, the length of a segment used in HCCL detection procedure can significantly vary. If the HCCL method is not robust with respect to the changes in segment length, markedly different hot spot list can be obtained depending without the change in collision history.

2.1.3 Issues related to using Average Annual Daily Traffic (AADT) Volume

SPF used by Caltrans (Caltrans, 2002) and the ones included in Highway Safety Manual (HSM) (AASHTO, 2010) only use average annual daily traffic (AADT) volume as an explanatory variable. This, however, does not mean that AADT is the only explanatory variable that shall be included developing SPF. Other studies showed that including additional explanatory variable often improved the performance of SPF (Garber et al., 2010; Tegge et al., 2010). However, seen from DOT, developing database to keep track of values of the additional parameters on state roadway system is cost-prohibitive. Therefore, only traffic volume is often included in SPFs used by government agencies.

Both the SPFs used by Caltrans and the ones included in HSM implicitly assume that the AADT measured at sporadic locations along the freeway remain constant within a segment (i.e., section of freeway within a same roadway group further segmented based on the changes in the value of the common feature compared to adjacent segments). This assumption about constant AADT within a segment is often violated when there are ramps included within a segment (Kononov and Allery, 2003). It is also important to note that there can be more than 30% difference in reported daily traffic volume depending on the type of detectors used even if the data are collected at the same time and location. At the locations where conventional loop detectors are not installed, traffic volumes are typically collected once in every three years; only a few weeks during a year to estimate AADT. Therefore, AADT used in SPFs can be often plagued with both the large variance due to small number of samples and measurement error due to detector bias (Chung et al., 2007).

2.1.4 Missing Traffic Collision Data

In California, all vehicle collisions occurred on a public roadway are reported into Statewide Integrated Traffic Records System (SWITRS), which is owned and maintained by the California Highway Patrol (CHP). The information about the collisions occurred on Caltrans-owned facilities is then sent to Traffic Accident Surveillance and Analysis System (TASAS), and this has been employed as the collision data source in this study.

Theoretically, TASAS should be a subset of SWITRS. However, inconsistencies between TASAS and SWITRS are often reported due to errors introduced during the process of entering postmiles information in traffic collision report: the postmile information is entered manually later in time by someone who was not at the collision site at time of the event. In addition, according to NHTSA (2000), about 40% of traffic collision data are not being reported to the collision database due to concerns about insurance, legal repercussions or other procedural errors. The amount of missing traffic collision data in California has not been quantified.

2.2 Performance of two sets of SPFs

Traffic collision data along 663 miles of freeways from 2004 to 2008 were used to calibrate the parameters of SPFs for the highway group shown in Fig. 1(b). All SPFs were assumed to have the same functional form (AASHTO, 2010; Harwood et al., 2010; Tegge et al., 2010) (see Eq. (1)) and the parameters were estimated for each of the roadway group using negative binomial regression model. The values of the estimated parameters are shown in Table 1 including the overdispersion factor, *k*.

$$SPF_{O,RSIF} = SL \times e^{\alpha} \times AADT^{\beta} \qquad (1)$$

Where, α and β are regression parameters and *SL* is segment length. $SPF_{O,RSIF}$ is SPF for roadway group RSIF and subscript "$_O$" has been used to differentiate the existing Caltrans SPF with SPFs developed in present study. In referring Caltrans existing SPFs, subscript "$_C$" will be used and its roadway group information will be subscripted in similar manner. For an example, $SPF_{C,H66}$ will be used to refer Caltrans existing SPF for highway group 66. The regression parameters were estimated by the statistics program package R.

Table 1. Estimated Regression Parameters of SPF_O

Highway Group	Using Fatal and Injury data						Total					
	α		β		1/*k*		α		β		1/*k*	
	Est	Std. Err	Est	Std. Err	Est	Std. Err	Est	Std. Err	Est	Std. Err	Est	Std. Err
RSIF	-6.49	2.06	0.85	0.19	7.79	2.72	-8.58	1.74	1.14	0.16	7.57	2.23
USIF	-3.29	1.45	0.61	0.13	2.28	0.27	-4.21	1.41	0.81	0.13	1.97	0.19
UEIF	-11.25	1.18	1.32	0.10	3.69	0.28	-6.42	1.35	1.01	0.12	2.31	0.15

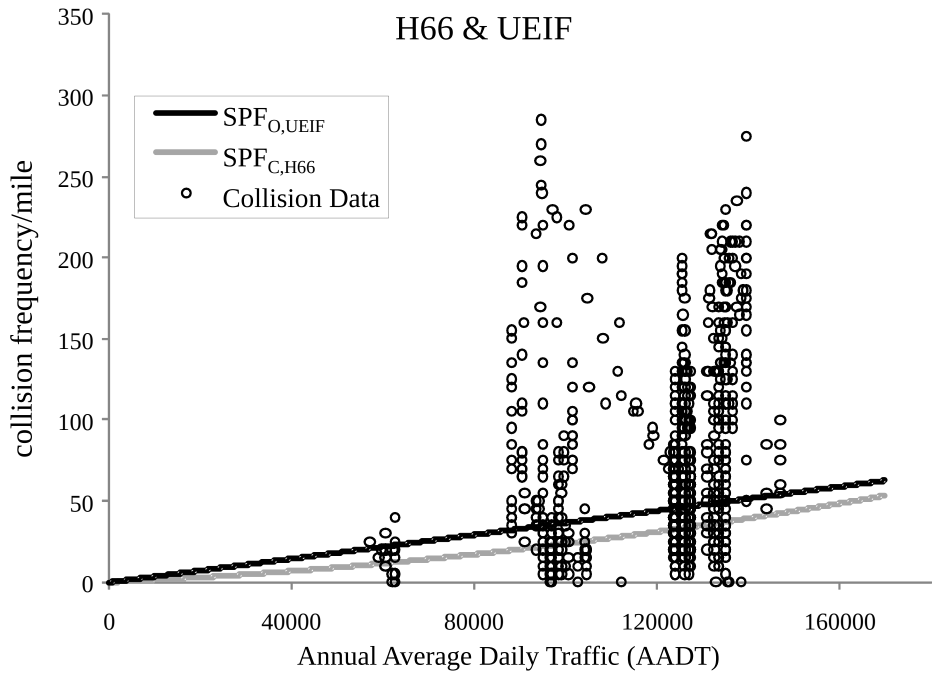


Fig. 3. $SPF_{O,UEIF}$ and $SPF_{C,H66}$ for the Corresponding Collision Data

The traffic collision and AADT data that meet both the description of H66 and UEIF are used to plot the circles in Fig. 3: in developing $SPF_{O,UEIF}$, the information from segments that meets UEIF description has been used. The black solid line is $SPF_{O,UEIF}$ and the grey solid line is $SPF_{C,H66}$. The performance of two different sets of SPFs has been evaluated using log-likelihood ratio test as shown in Eq. (2). *LL* in Eq. (2) denotes the Log-likelihood function. The difference of Log-likelihood for two models, *D*, approximately follows chi-square distribution with the degree of freedom determined by the difference of degree of freedoms between SPF_C and SPF_O. SPF_C is used as a null model and SPF_O as alternative model. The results of the test summarized in Table 2 and they indicate that SPF_O explains the variance in the data more appropriate than SPF_C in all the highway groups examined in present study.

$$D = -2LL(SPF_C) + 2LL(SPF_O) \quad (2)$$

Table 2. Difference of Log-likelihood of SPFs

	$LL(SPF_C)$	$LL(SPF_O)$	D	P-value
$SPF_{C,H55}$ & $SPF_{O,RSIF}$	-684.28	-681.63	5.30	0.0213
$SPF_{C,H56}$ & $SPF_{O,RSIF}$	-1761.47	-1663.60	195.73	0.0000
$SPF_{C,H61}$ & $SPF_{O,USIF}$	-2648.28	-2598.62	99.32	0.0000
$SPF_{C,H62}$ & $SPF_{O,UEIF}$	-2232.49	-2087.79	289.40	0.0000
$SPF_{C,H64}$ & $SPF_{O,USIF}$	-2988.69	-2572.61	832.15	0.0000
$SPF_{C,H65}$ & $SPF_{O,UEIF}$	-9294.89	-7153.34	4283.11	0.0000
$SPF_{C,H66}$ & $SPF_{O,UEIF}$	-10534.45	-5050.47	10967.97	0.0000
$SPF_{C,H67}$ & $SPF_{O,UEIF}$	-9080.48	-1091.56	15977.84	0.0000

3. Description of Screening Methods

Sliding Moving Window (SMW), Peak Searching (PS), and Continuous Risk Profile (CRP) are different methods for determining the endpoints of a *site*, and the data requirements for using each method are the same. After the endpoints are determined in each method, a same guideline can be applied to prioritize the detected sites for safety investigation.

In present study, the data within sites identified in each of these methods are used to estimate excess expected average crash frequency with Empirical Bayes (EB) adjustment (Hauer et al., 2002) which is the difference between the expected average crash frequency with EB adjustment (see black circle in Fig. 4) and SPFs. This estimate has been considered as the potential for safety improvement (PSI) of a site. The expected average crash frequency with EB adjustment is calculated by EB method using SPF and observed collision frequency within the sites (AASHTO, 2010). PSI of each site was computed using both SPF_C and SPF_O, and used to rank the sites for safety investigation.

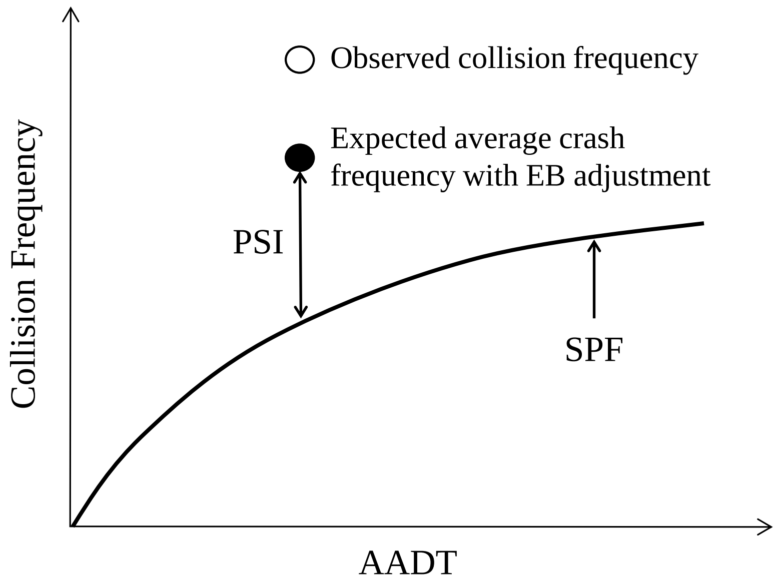


Fig. 4. PSI Estimated for Three Network Screening Methods

In SMW method, PSI, which is the vertical difference between SPF and observed collision frequency within a window of a fixed size (see w in Fig. 5) readjusted using EB method (see the black circle in Fig. 4) (AASHTO, 2010), is first estimated at the start of a segment (see L in Fig. 5). Then, the PSI of the next window is estimated in the same manner after offsetting the window by a small increment (see *l* in Fig. 5), and the procedure is repeated (see the dotted box in Fig. 5) until the window reaches the end of segment. The PSIs from the windows at each position within a segment are then compared, and the maximum PSI value is assigned to the segment to represent the potential for collision reduction for the whole segment. The window can span over two or more segments when the length of segment is small compared to the window size. The size of the site detected in SMW is equal to segment length.

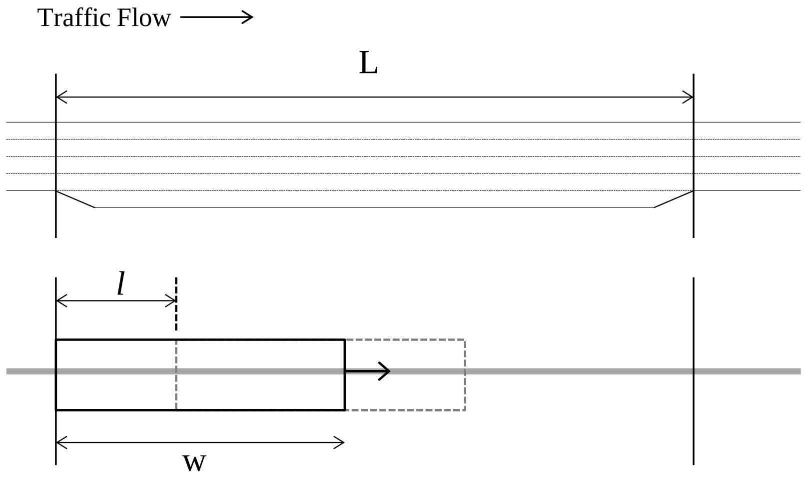


Fig. 5. Sliding Moving Window (SMW) Method

PS method first subdivides the segment (see L in Fig. 6) into small windows of similar lengths (see w_1 in Fig. 6). The data that belongs to each of the window is used to estimate the PSI (see Fig. 4) in the manner described in preceding paragraphs. Then the estimated PSIs are subjected to precision testing using the coefficient of variation (CV) (Eq. (3)) as described in HSM (AASHTO, 2010). A large CV means a low level of precision and a small CV indicates a high level of precision. If CV value of a window is lower than or equal to the CV limiting value, it means that the PSI of the window satisfies the desired precision level. According to HSM (AASHTO, 2010), appropriate CV limiting value is 0.5.

$$\text{Coefficient of Variation (CV)} = \sqrt{Var(PSI)}/PSI \qquad (3)$$

If the PSI for at least one of windows satisfies the desired precision level, the maximum PSI value from all of the windows satisfying the desired precision level is chosen to represent the crash reduction potential for the whole segment. If none of PSIs for the windows meets the desired precision level, the size of window is increased (see w_2 in Fig. 6) and then the calculation is repeated to assess the precision of the PSI. This procedure continues until a maximum PSI with the desired precision is found or the size of the window reaches the length of entire segment (see W_N in Fig. 6). Similar to SMW, the chosen maximum PSI value represents the potential for collision reduction for the whole segment. The size of detected site in PS method is the same as the segment length.

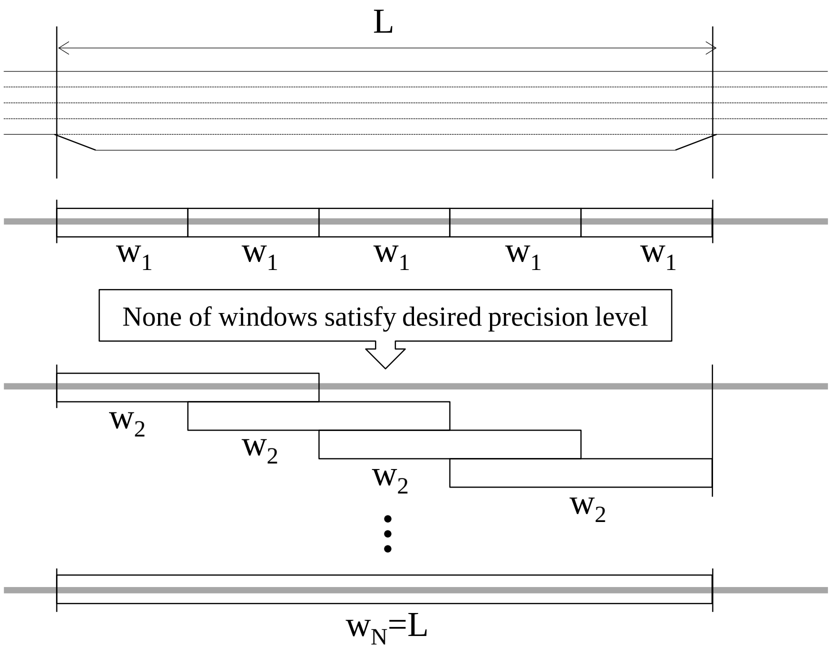


Fig. 6. Peak Searching (PS) Method

CRP method first filters out the random noise in the data using weighted moving average technique and continuously plots the collision risk profile along the freeway (see the bold line labeled CRP in Fig. 7(b)) (Chung et al., 2009, 2011). Then, the predicted collision frequency based on the AADT for the segment is obtained from corresponding SPFs (see F_1 and F_2 in Fig. 7(a)). The unit of the value obtained from SPF is converted to the unit comparable to CRP to be plotted together as shown in Fig. 7(b) (see the dotted line labeled SPF). Where CRP exceeds the dotted line (see location labeled s and e) defines the endpoints of a site. Thus, the size of the site defined in CRP is not influenced by endpoints of segments. The area between the horizontal dotted lines (i.e., SPFs) and CRP denotes the excess crash frequency (see the light grey area labeled A in Fig. 7(b)). The area enclosed by s, e, and the vertical dotted lines (see the dark grey area labeled B in Fig. 7(b)) denotes the crash frequency of the SPFs. A + B is the observed collision (see the white circle in Fig. 4), which is readjusted using EB method (see the black circle in Fig. 4) to estimate PSI in the same manner to rank sites for safety investigation (see Fig. 4).

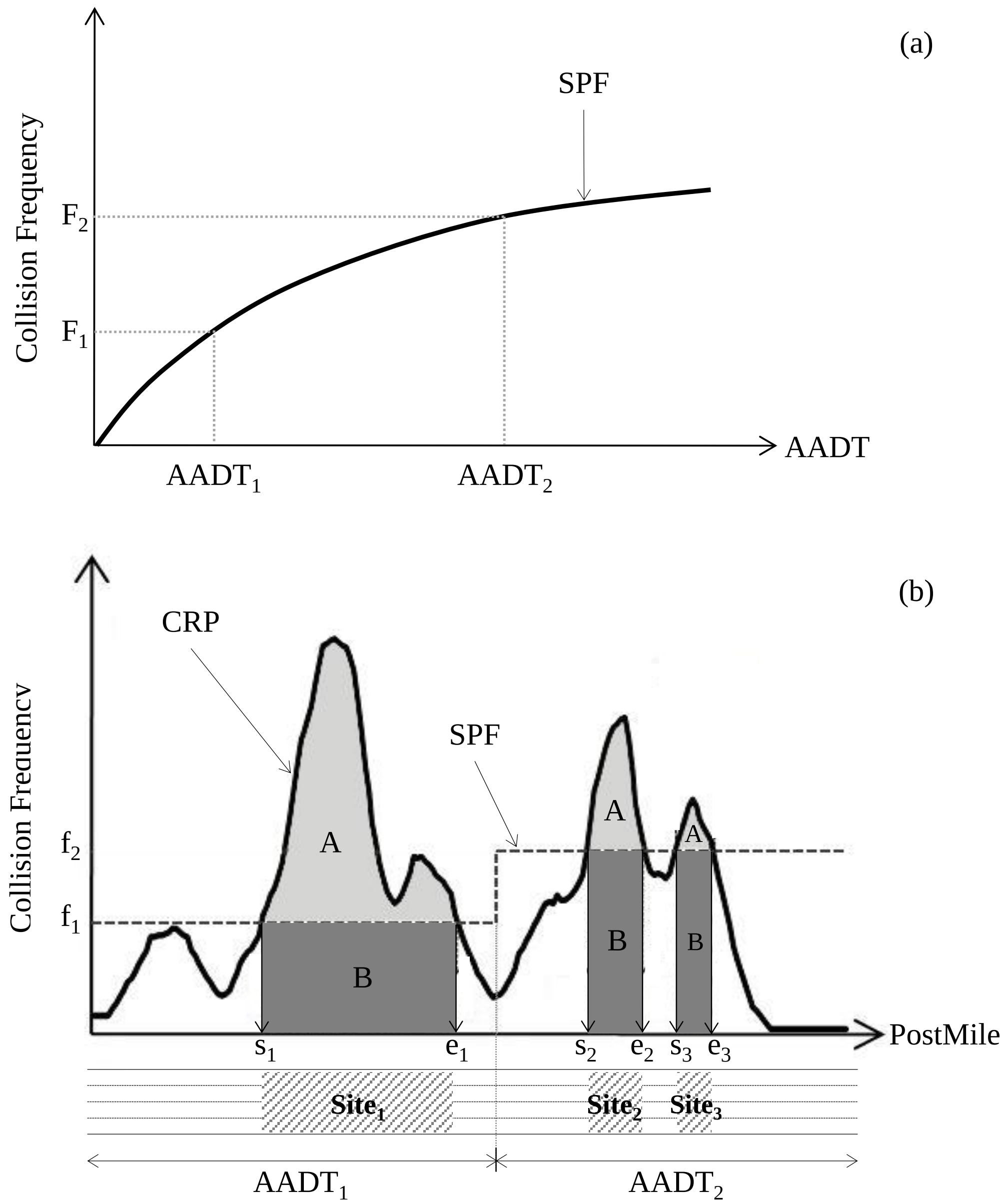


Fig. 7. Continuous Risk Profile (CRP) Method: (a) Predicted Collision Frequency, (b) Site Detection of CRP

4. Findings

4.1 Ranking Sites Based on Its Potential for Crash Reduction

Caltrans currently uses SMW method and critical rate as the measure (AASHTO, 2010) to detect hot spots. The detected spots are not ranked at the screening stage, but they are ranked later, based on cost benefit ratio of potential countermeasures estimated by safety engineer. The critical rate being used by Caltrans is 99.5 percentile and the sites where collision rate exceeds the threshold are flagged as potential safety investigation locations (Caltrans, 2002). Both critical rate and PSI are one of the several potential measures that can be used as a guideline for determining sites for safety investigation (AASHTO, 2010).

All the sites that are flagged using SMW method do not necessarily end up being reported to Caltrans quarterly hot spot list known as Table C. For the purpose of illustration, these initial sets of sites that are detected based on critical rate will be referred as *generic* Table C list from hereon. This list is superset of final Table C and includes many sites that had been reported in the previous quarter of Table C, but not yet had chance to be investigated by safety engineer: when the collision patterns are reproducible, the sites detected in previous quarters are often detected again in the following quarter. Caltrans currently applies additional procedure to *generic* Table C list to eliminate those repeat locations prior to finalizing Table C. The locations detected in previous three quarters are excluded and some of the adjacent sites are combined as one site during the additional procedure.

Generic Table C list, for an example, reported 46 sites based on 12 months collision data in 4th quarter of 2008, whereas final Table C for the same period reported only 4 sites. Such significant differences in the number of sites between *generic* Table C list and final Table C are observed in each quarter. Since the list of hot spots in final Table C reflects the additional change described in the previous paragraph, simply comparing the list of sites detected in three methods with Table C list without applying the same additional procedure would make SMW, PS and CRP methods appear to have higher false positive rate than existing Table C procedure.

The final Table Cs from each quarter from 1th quarter of 2007 to 4th quarter of 2008 are used to evaluate the performance of three different methods and these lists are collectively referred as confirmed hot spots (CHS) in the proceeding sections: CHS can be considered as subset of true hot spots (THS) which cannot be obtained in an empirical study. The sum of all the site lengths in CHS used in this study was 6.5 miles. The findings from comparing the performances of these methods are discussed in the next section.

4.2 Performance of Each Segmenting Method

Three different performance measures have been developed to evaluate the performance of SMW, PS and CRP methods. These performance measures compare: (i) the number of sites that each method requires to detect CHS; (ii) the number of miles that safety engineers need to investigate to detect CHS; and (iii) the changes in hot spot detection efficiency ($HSDE_r$) (i.e., the ratio between number of miles that belongs to CHS and miles detected in each methods up to rth ranked site) of each method with respect to changes in ranks.

The performances of SMW, PS, and CRP methods can be explained with the aid Figs. 8 and 9. Figs. 8(a), 8(b), and 8(c) show the performances of each method using SPF_C and LS whereas Figs. 8(d), 8(e), and 8(f) show the corresponding results using SPF_C and SS. Then, after replacing SPF_C with SFP_O, changes in the performance of each method were evaluated under LS and SS. These findings are summarized in Fig. 9. In all figures, dark dotted lines represent the performance of SMW method. The grey and black solid lines show the performances of PS and CRP methods, respectively.

Figs. 8(a) and 8(d) graphically show the number of sites required to detect all sites listed in CHS using SMW, PS, and CRP methods under two different segment definitions, LS and SS. As an illustration, see the dotted grey vertical line that points 72 in the x-axis (see Fig. 8(a)) while its corresponding y-axis value points at 6.5 miles which is the sum of the length of all the sites in CHS. This implies that if a state agency employed SMW method, it would have been required to investigate top 72 sites (based on PSI value) to properly investigate all the sites listed in CHS. Likewise, utilizing PS and CRP would have required investigating top $66^{th}$and 57^{th} sites respectively under LS. Thus, these ranks marked with vertical arrows in Fig. 8(a) can be considered as the number of sites that each method requires to investigate to detect all CHS. Under SS, the number of sites required to detect CHS markedly increased from 72 to 114 in SMW and 66 to 113 in PS methods. However, the number of sites required to detect CHS under LS and SS did not change using CRP method. This is due to the fact that the length of site changes when segment length changes in SMW and PS while the length of the site is independent of segment length in CRP method.

When SPF_C was replaced with SPF_O, the number of sites required to detect CHS by SMW and PS methods were notably decreased from 72 to 30 and 66 to 31: this is about 50% reduction. Similarly the number of sites required by CRP method reduced from 57 to 54. Such improvement could contribute to using SPFs that better fit in the traffic collision data. Changing segment definition from LS to SS, the number of site required by SMW and PS methods again markedly increased to 76 and 68, respectively, while that of CRP method did not change.

The number of sites required for safety investigation reflects the number of times that safety investigators need to visit sites in person. If the cost associated with site investigation is constant regardless of the length of the site, using SMW method with SPF_O under LS would result in the minimum cost. However, this is not likely the case in practice. The cost associated with investigating a longer site will be higher than the cost of investigating a shorter site: an investigator needs to spend longer time at the site and will be exposed to live traffic for a longer duration. Therefore, the total number of miles required to investigate to detect all CHS needs to be considered at the same time.

Figs. 8(b) and 8(e) shows that CRP methods required the investigation of 37 miles in its 57 sites under LS and SS assumptions using SPF_C. PS and SWM required the investigation of 61 and 69 miles under LS. Both PS and SWM required investigation of 67 miles under SS. Replacing SPF_C with SPF_O resulted in reducing the number of miles that needs to be investigated to detect all CHS in all three methods. Under LS using SPF_O, CRP required 28 miles while PS, SMW required 58 and 67 miles respectively; this is reduction of 9 miles for CRP, 3 miles for PS, and 2 mile for SMW compared to under LS using SPF_C (see Fig. 9(b)). Under SS using SPF_O, CRP, PS and SWM required investigation of 28, 56 and 66 miles, respectively (see Fig. 9(e)). Note that under LS using SPF_O, PS and SWM are requiring less number of sites to be invested, however, the number of miles that these two methods are requiring to be investigated is significantly higher than that of CRP.

The slope of the line connecting the origin and the end point of each graph represents hot spot detection efficiency (HSDE) of each method: the slope is the ratio between the numbers of miles that is in CHS per mile identified by each method. For an example, CRP methods identified 37 miles (see Figs. 8(b) and 8(e)) in its 57 sites under LS and SS assumption using SPF_C. CRP's overall HSDE is 17%. The performances of SMW and PS methods under LS and SS are also shown in the figures.

Replacing SPF_C with SPF_O resulted in improving the HSDE of CRP by 6% while the HSDE of SMW remains unchanged. The HSDE of PS showed improvement of 2%. Recall that the length of site in CRP method is determined by SPF. Using SPF_O resulted in vertically shifting the dotted line upward without surpassing the peaks (without missing hot spots) in each site shown in Fig. 7(b). Thus, the HSDE of CRP method was significantly improved by using SPF_O while those of SMW and PS methods remain unchanged. The HSDE of CRP outperformed SMW and PS methods in all four cases.

HSM (AASHTO, 2010) states that after ranking the site, both SMW and PS methods can subsequently select segments for further investigation. Such subsequent procedure was not considered in comparing the HSDEs of SMW and PS methods in present study since this would require dealing with multiple collision concentration locations within each site. Depending on the procedure chosen for the subsequent analysis, it can both increase and decrease the HSDEs of SMW and PS methods (Kononov, 2002). It is also important to note that the magnitudes of HSDEs of SMW, PS, and CRP methods are all underestimated for the reasons explained in section 4.1 of this paper.

One of the issues in SMW and PS methods observed during the analysis is that PSI of a whole segment is represented by PSI of the maximum window within the segment (AASHTO, 2010). Suppose there are three segments A, B, and C. Segment A has windows that display 1^{st} and 3^{rd} highest PSI value; segment B has 4^{th} and 5^{th}; and segment C has 2^{nd} and 6^{th}. Then, segment A will be ranked 1^{st}, C as 2^{nd}, and B as 3^{rd}. Suppose SMW and PS methods employ methods for subsequently selecting one site (or limited number of sites) within each segment for the safety investigation. This subsequent procedure will then select sites that display 1^{st} (from segment A), 2^{nd} (from segment C), and 4^{th} (from segment B) PSI rather than selecting sites with top three PSIs. Such issue can be resolved if the PSI of all the sites from different segments are compared rather than only the maximum PSI value from each segment. Notice how SMW and PS then essentially become similar to CRP method as they reduce the size of the segment.

The HSDEs of each method with respect to different ranks, $HSDE_r$, are also evaluated and they are shown in Figs. 8(c), 8(f), 9(c), and 9(f). Except the case shown in Fig. 8(f), $HSDE_r$ of CRP method remained higher all the time in the other three cases. $HSDE_r$ of SMW and PS methods peak before they reach 5^{th} and 3^{rd} ranked sites, respectively. The difference between $HSDE_r$ among the three methods diminishes after reaching 21^{st} ranked site.

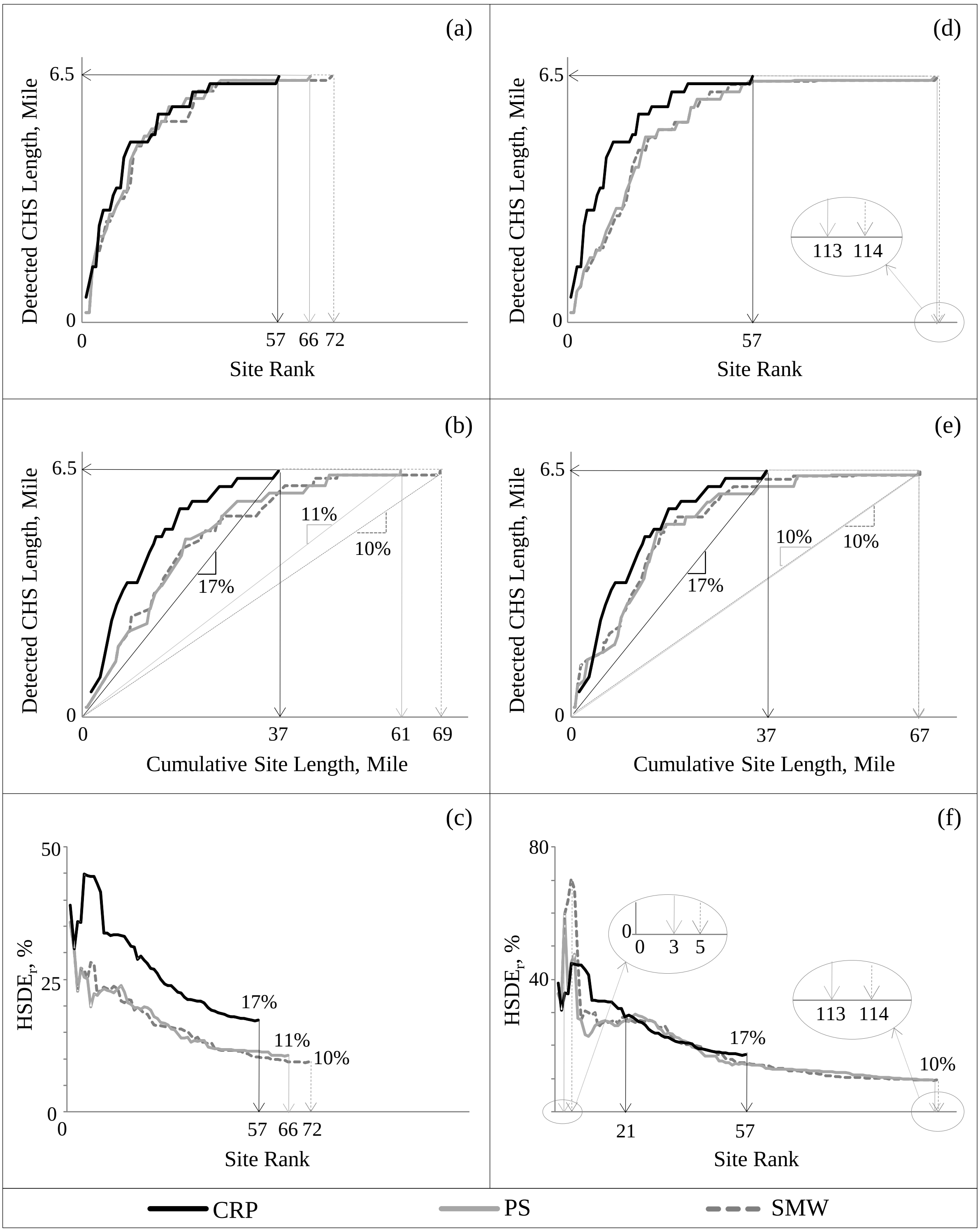


Fig. 8. Performance Plots of Three Network Screening Methods Using SPF_C: (a) Number of Sites Required to Detect CHS Using LS, (b) HSDE of Each Method Using LS, (c) Change in $HSDE_r$ with Respect to Change in Rank Using LS, (d) Number of Sites Required to Detect CHS Using SS, (e) HSDE of Each Method Using SS, (f) Change in $HSDE_r$ with Respect to Change in Rank Using SS

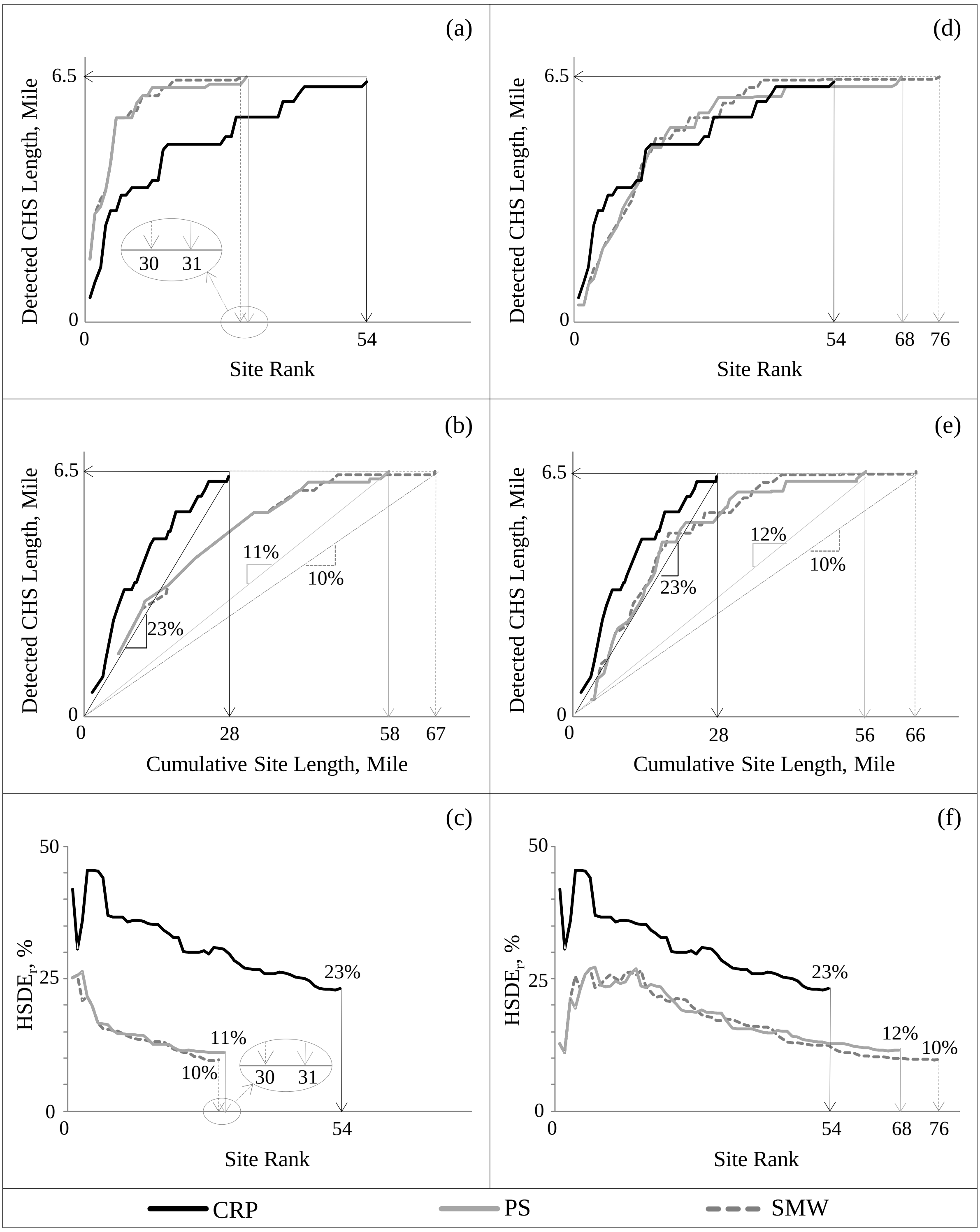


Fig. 9. Performance Plots of Three Network Screening Methods Using SPF_O: (a) Number of Sites Required to Detect CHS Using LS, (b) HSDE of Each Method Using LS, (c) Change in $HSDE_r$ with Respect to Change in Rank Using LS, (d) Number of Sites Required to Detect CHS Using SS, (e) HSDE of Each Method Using SS, (f) Change in $HSDE_r$ with Respect to Change in Rank Using SS

5. Concluding Remarks

The performances of three different methods for identifying hot spots have been compared using empirical data from California. All three methods require traffic volume, collision data and SPF for their analysis and they only differ in a way how they determine the endpoints of a site: SMW and PS predefine the start and end location of a roadway segment only based on roadway attributes while CRP lets the SPF and traffic collision data to define the endpoints of a site. The same guideline, PSI, excess expected average crash frequency with Empirical Bayes (EB) adjustment has been used to rank the sites detected from each method for safety investigation.

To evaluate the robustness of these methods, different set of SPFs and segment definitions were applied together with SMW, PS and CRP methods. It is important to note that the segment definition can vary from state to state since there exist a number of different guidelines that can be used to categorize roadway group and define the endpoints of a segment. The difference in segment endpoints will change the data included in each of the site which are used to prepare the data points in developing SPFs. Such change will affect the values of estimated parameters regardless of which models were used: Poisson or Negative Binomial. The functional form of SPFs may also change. More importantly, different segment definitions can significantly change the length of the site detected in SMW and PS methods.

Decreasing the length of the segment from LS to SS resulted in marked increase in the number of sites that need to be investigated to detect all the sites in CHS using SMW and PS methods while that of CRP did not change (see Figs. 8(a), 8(d), 9(a), and 9(d)). CRP method required 57 sites to detect all the sites in CHS using SPF_C under LS and SS definition, while SMW and PS methods required 72 and 66 sites under LS, and 114 and 113 sites under SS, respectively, to detect all the sites in CHS; similar pattern was observed when SPF_C was replaced with SPF_O.

Using SPFs that better fit in the traffic collision data improved the performance of all three methods. When SPF_O were used instead of SPF_C, the numbers of sites required by SMW and PS methods to detect CHS were reduced roughly by 50% while than that of CRP was reduced by 5%. Using SPF_O resulted in vertically shifting the dotted line up or downward at different segments in Fig. 7(b). The difference in SPF_O and SPF_C did not significantly alter the number of sites required by CRP method to detect all the sites listed in CHS. However, using different SPF markedly changed the number of sites required by SMW and PS. Such unique property of CRP can be especially useful when the input data for SPFs are inherently plagued with measurement error and some of the explanatory variables in SPFs had to be omitted due to lack of database.

The hot spot detection efficiency (HSDE) of CRP outperformed SMW and PS methods in all four cases. This indicates that CRP method has potential for reducing the amount of time that a safety engineer needs to spend for sites investigation and be exposed to live traffic. The HSDEs of SMW and PS method did not change much with respect to different segment definition and whether SPF_O or SPF_C were used. CRP's HSDE was improved from 17% to 23% when SPF_O were used instead of SPF_C.

The HSDEs of SMW and PS methods can be further improved by employing subsequent analysis to narrow down the sites within each segment for safety investigation. Such additional procedures can make SMW and PS methods converge to CRP method.

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