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Cross-Section Designs for the Safety Performance of Buffer-Separated High-Occupancy Vehicle (HOV) lanes

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ABSTRACT

High-occupancy vehicle (HOV) lanes have been deployed as a tool for traffic management in urban freeway systems to improve reliability and mobility of trips. As they are planned to traverse crowded urban areas, it is often difficult to acquire sufficient right-of-way for retrofitting HOV lanes to existing freeway systems with recommended cross-sectional design. The present study proposes a methodology to determine the optimal set of cross-sectional design for safety performance by evaluating individual impact of each design element on safety as well as tradeoffs between them. Detailed collision data of concurrent-flow buffer-separated HOV lanes along with their geometric features and traffic flow data were analyzed to estimate collision predictive models for HOV and the adjacent general purpose lanes by injury types. These models were used to determine the set of cross-sectional design elements that minimizes the expected collision occurrences. As a case study, a real freeway corridor where converting continuous to buffer-separated types was underway was selected to demonstrate the applicability of the proposed method. This case study shows that the method can assist to determine cross-section design of HOV facilities for safety based on currently available geometric space.

1. INTRODUCTION

High-Occupancy Vehicle (HOV) lanes have been deployed in congested urban freeways for the last several decades as a congestion management strategy. Various types of HOV configurations and operation schemes, in accordance with commute patterns in local regions, have been implemented. Among those configurations, concurrent-flow buffer-separated lanes consist 48% of all the HOV lane-miles with an increasing trend as of 2001 (*1*). Concurrent-flow buffer-separated HOV lanes operate in the same direction of travel as General Purpose (GP) lanes but are separated from the GP lanes by buffer zones, permitting maneuvers to enter and exit only at specified ingress and egress sections.

For the safety aspects of HOV facilities of this type, wider space allocated for HOVs was found to provide better safety performance (*2*, *3*). The total amount of space available for the use of HOVs is referred to as the total width, which is a combination of median shoulder, HOV lane and buffer zone. Since HOV lanes are generally deployed in densely developed metropolitan areas, however, few projects have enough right-of-way to allocate space for HOVs as recommended by these earlier studies (*2*, *3*) and design guidelines (*4*, *5*, *6*).

To install HOV facilities within the limited right-of-way, thus, tradeoffs between the components of total width are inevitable (e.g. narrowing lane width for inserting wide buffer, converting median shoulder width to buffer or lane, etc.). Only a few State Departments of Transportation have developed general guidance to prioritize such tradeoffs in designing cross-sections of HOV facilities (*5*, *6*). Even these guidelines were not developed based on quantitative consideration of safety aspects of design elements in HOV facilities. As growing concerns about the safety consequences of highway designs, Highway Safety Manual (HSM) (*7*) has been published to provide factual information on highway designs for traffic safety. This latest version of HSM offers guidelines only for limited types of highway facilities but does not include those for HOV facilities.

Some recent studies evaluated design elements that have impacts on traffic crashes in HOV facilities. Cooner and Ranft (*2*) analyzed traffic crash reports collected from buffer-separated HOV facilities in Texas and found that greater total width is associated with enhanced safety performance. Jang *et al.* (*3*) examined the relation between shoulder and total widths vs. crash rates in HOV lanes as part of their comparative study between safety performance of contiguous and buffer-separated HOV facilities in California. In this study, it was shown that crash rates tended to diminish nonlinearly as shoulder and total widths increase. However, none of the previous studies provides a means of quantifying balance or tradeoffs between cross-sectional design elements in HOV facilities.

This present study suggests collision predictive models for HOV facilities and, by using these predictive models, selects a set of numerical cross-sectional design variables that minimizes expected collision occurrences. The remainder of this paper is organized as follows: Section 2 provides descriptions of collision data and sites used in this study. Section 3 specifies models for different injury levels and lanes, and estimates parameters. Section 4 provides methodology to select the optimal set of design elements minimizing expected safety costs. Section 5 applies the proposed method to a case study to exemplify the potential use of the methodology. The final section discusses the implications of this study and future research directions.

2. SITE AND DATA DESCRIPTIONS

For more detailed and accurate information, multiple data sources were combined. The data used for this study are composed of four different data sources: i) Traffic Accident Surveillance and Analysis System (TASAS), ii) document retrieval system, iii) photolog, and iv) Freeway Performance Measurement Systems (PeMS). They are described and explained below.

Traffic Accident Surveillance and Analysis System (TASAS)

TASAS is a computerized collision database maintained by the California Department of Transportation (Caltrans) (*8*). Within TASAS, there are two different data sets about collisions and geometric attributes. Each record of collision data has detailed information on a collision itself such as time, location (postmile and lane), road and weather conditions, victims, primary collision factor, type of the collision, and many others. Meanwhile, geometric attributes include a set of geometric and location information on freeway segments – freeway segments are partitioned wherever at least one of geometric attributes alters such that geometric attributes are identical within each freeway segment.

Document Retrieval System (DRS)

Built plans and survey files were obtained from Caltrans DRS through the Caltrans intranet. Since some of the geometric variables associated with HOV lanes are unavailable from TASAS, those variables (buffer widths, HOV lane width and ingress/egress locations) were supplemented by the data manually extracted from built plans and survey files.

Photolog

Caltrans Photolog is a series of photos recorded in accordance with post mile in the California state freeway system (*9*). Since DRS does not provide data covering all the study routes, HOV-related geometric variables were extracted from photo images for some of the freeway sections which are not covered by DRS.

Freeway Performance Measurement System (PeMS)

PeMS is a tool that collects real-time traffic data from sensors (e.g. loop detectors) and provides traffic information on-line (*10*). To obtain lane-by-lane traffic volumes (in HOV and the adjacent GP (left) lanes), traffic volume data were downloaded from PeMS database and aggregated to compute Annual Average Daily Traffic (AADT) for each freeway segment in the study routes.

Three years (from 2005 to 2007) of collision data from 13 routes stretched slightly over 153 miles in Southern California were queried from TASAS collision data set (See list of corridors in Table 1 and their geographic locations in Figure 1). For each freeway segment, the number of collisions was counted by injury types (injury and Property Damage Only (PDO)[1]) and also by lane locations (HOV and the adjacent GP (left) lanes[2]), and its corresponding geometric attributes and AADT data were recorded accordingly. These counts were used as outcome variables; and geometric attributes and AADT data were input as independent variables for model estimation. Note that the lengths of the routes are measured in miles (≈ 1.61 kilometers) to be consistent with the post mile numbers contained in the TASAS database.

TABLE 1 List of the Study Corridors

District	County	Route	Direction	Start Postmile	End Postmile	Length (miles)
7	Los Angeles	105	E	2.2	17.3	15.1
7	Los Angeles	105	W	17.3	2.2	15.1
7	Los Angeles	210	E	25.0	37.6	12.6
7	Los Angeles	405	N	7.9	13.8	5.9
7	Los Angeles	405	S	13.8	7.9	5.9
7	Los Angeles	405	S	26.0	13.0	13.0
7	Los Angeles	605	N	0.2	7.0	6.8
7	Los Angeles	605	N	10.8	20.7	9.9
7	Los Angeles	605	S	7.0	0.2	6.8
7	Los Angeles	605	S	20.7	10.8	9.9
12	Orange	5	N	8.1	29.0	20.9
12	Orange	5	S	29.0	8.8	20.2
12	Orange	57	S	22.5	11.2	11.3

[1] Injury types are differentiated because their magnitudes of overall costs for the society are different (medical costs, life expectancy, time delay, etc.). (*11*, *12*)

[2] Safety performance of the HOV lane itself and the adjacent GP (left) lane were found to be most relevant to HOV configurations (*2*, *3*). Thus, only collisions that occurred in HOV and left lanes were included in the analysis of this paper.

FIGURE 1 Map of the Study Corridors

3. MODEL SPECIFICATION AND ESTIMATION

This section provides the description of collision predictive models. Four different collision predictive models were specified by injury types and lanes (HOV and the adjacent GP (left) lanes) – i) PDO collisions in HOV lane; ii) injury collisions in HOV lane; iii) PDO collisions in left lane; and iv) injury collisions in left lane, and the associated model coefficients were estimated by using negative binomial regression.

Negative Binomial Regression

This section reviews theoretical background of traffic collision process and selects the statistical model that is appropriate for this study. The proof and derivations are based on Larsen and Marx (*13*) and similar discussions about the collision process can also be found in previous literature (*14*). Suppose that a vehicle passing a point location of freeway is a Bernoulli trial[3] and the occurrence of a collision at the

[3] It is considered as a Bernoulli trial because it can be viewed as an experiment with only two possible outcomes: collision and non-collision.

location is a random event with a certain probability, p. Then, the probability of X collisions out of N vehicles passing the location (i.e. trials) is expressed as $P(X=x)=\binom{N}{x}\cdot p^x\cdot(1-p)^{N-x}$. As the number of trials, N, becomes large, the probability converges to Poisson distribution:

$$\lim_{N\to\infty}P(X=x)=\lim_{N\to\infty}\binom{N}{x}\cdot p^x\cdot(1-p)^{N-x}=\lim_{N\to\infty}\frac{N!}{(N-x)!\cdot x!}\cdot\left(\frac{\lambda}{N}\right)^x\cdot\left(1-\frac{\lambda}{N}\right)^{N-x}$$
$$=\lim_{N\to\infty}\underbrace{\frac{N!}{(N-x)!\cdot N^x}}_{\approx 1}\cdot\left(\frac{\lambda^x}{x!}\right)\cdot\underbrace{\left(1-\frac{\lambda}{N}\right)^N}_{\approx\exp(-\lambda)}\cdot\underbrace{\left(1-\frac{\lambda}{N}\right)^{-x}}_{\approx 1}=\left(\frac{\lambda^x}{x!}\right)\cdot\exp(-\lambda)$$

Where, $\lambda = N\cdot p$

Therefore, the number of collisions occurred at a certain location within a sufficiently long duration of time – by doing so, to be able to observe sufficient number of passing vehicles – follows the Poisson distribution. If probability, p, is constant (thus, $\lambda = N\cdot p$, known as Poisson rate is also constant) during the observation, it is a natural choice to use Poisson regression in modeling collision frequency with AADT and other geometric characteristics. Realistically, however, this assumption is often violated due to heterogeneity in trials due to heterogeneous drivers' behavior, spatially and temporally varying characteristics, changes in traffic conditions, etc. This violation results in larger sample variance, VAR(λ), than the sample mean, E(λ), which, in turn, biases estimates from Poisson regression.

Since Negative Binomial (NB) probability mass function has a parameter, y, in addition to rate parameter, λ, that renders it more suitable for representing a collision process, NB regression can properly model the collision occurrences even when VAR(λ) $\geq$ E(λ). NB distribution is a distribution of the number of collisions, X, in a sequence of passing vehicles prior to the predetermined number of non-collisions, y. The probability can be expressed as $P(X=x)=\binom{y+x-1}{y-1}\cdot p^x\cdot(1-p)^y$. When y goes to infinity, the probability mass function of NB distribution becomes that of Poisson distribution as shown below.

$$\lim_{y\to\infty}P(X=x)=\lim_{y\to\infty}\binom{y+x-1}{y-1}\cdot p^x\cdot(1-p)^y=\lim_{y\to\infty}\frac{\lambda^x}{x!}\cdot\underbrace{\frac{\Gamma(x+y)}{\Gamma(y)\cdot(y+\lambda)^x}}_{\approx 1}\cdot\underbrace{\frac{1}{\left(1+\frac{\lambda}{y}\right)^y}}_{\approx\exp(\lambda)}$$
$$=\left(\frac{\lambda^x}{x!}\right)\cdot\exp(-\lambda)$$

Where, Γ(n) = (n-1)!, Gamma function.

NB distribution[4] can accommodate Poisson distribution while relaxing the assumption VAR(λ) = E(λ). Thus, modeling collision frequency with NB regression is a more reasonable choice and, thus, widely applied in many previous studies (*15*, *16*, *17*). Other than Poisson and NB regressions, a couple of other regressions, Zero-Inflated Poisson and Zero-Inflated NB regressions, have also been used in estimating coefficients of collision models when there are excess zero outcomes in the data (See more details in Lord et al. (*14*)). In the present study, the NB regression was found to be adequate for the collected data. The coefficients for NB regression models can be estimated by maximum likelihood estimation, the process of which is readily available in commercially available software such as STATA and Limdep.

Model Estimates

For coefficients' estimation, 30% of non-homogeneous and non-contiguous freeway segments from 153 miles of freeway stretch were randomly selected to avoid the inclusion of potentially correlated samples while still having enough variability across samples. This caution was taken because samples collected from nearby freeway segments may be auto-correlated (*18*). The three-year study period (from 2005 to 2007) was considered to be a sufficient duration to observe enough trials (passing vehicles). Since this study focuses on the cross-sectional designs of HOV facilities only for closed sections that are physically separated from the GP lanes, geometric variables only relevant to the safety performance of these sections were included. Variable selections were fully relied on empirical findings from previous literature (*2*, *3*). Consistent with these previous findings, the estimated models show that the set of selected geometric variables along with AADT can significantly represent the collision occurrences.

The functional forms were determined after examining *Empirical Integral Functions* for all variables, the method proposed by Hauer and Bampo (*19*). The method indicates that all variables can be specified by forms of power functions. Given these functional forms, thus, coefficients were estimated by NB regression using the collision and geometric characteristics data. Table 1 summarizes the estimates of coefficients.

The coefficients reflect the elasticity of the corresponding variables. More specifically, the coefficients indicate the ratio of one unit change in an independent variable to the change in the expected collision frequency, depending on the functional relation between the independent variable and collision frequency. The signs of the coefficients represent how the variables are associated with the collision frequency – negative sign means negative correlation and positive sign means positive correlation – and the numbers signify the magnitude of changes – larger number indicates larger changes in collision frequency by one unit change in one variable.

[4] Mean is λ and variance is $\lambda+1/y\cdot\lambda^2$ where, $1/y$ is often called over-dispersion parameter. When $1/y$ becomes zero, the variance equals λ.

The significance of estimated coefficients appears to be dependent on the sample size and the number of collisions observed – predictive models for PDO collisions perform better due to higher number of collisions (less likely to have observations of zero collision), and coefficients of categorical variables with larger samples have more significant estimates. Overall, the estimates have reliable and reasonable outcomes.

- **HOV lane width:** Wider HOV lane width tends to be associated with fewer number of collision frequencies except for the case with 13ft width. This is because there is not enough number of freeway segments with 13ft-wide HOV lanes (in the collected samples) so that the coefficients for 13ft HOV lane widths were not statistically significant.
- **AADT:** Higher AADTs in HOV and left lanes, except injury collisions in left lane, are positively related to collision frequency, which means that the freeway segments with more traveling traffic tend to have higher collision frequency. However, injury collisions in left lane show an opposite pattern negatively correlated albeit with a very small number: This implies that higher traffic leads to fewer collisions in the left lane but the variation is not substantial. The casual effect is not investigated in this study but one interpretation of this predicted effect is that collisions are likely to be more severe when traffic is light. It may also imply that the collisions occurring in left lanes are not substantially affected by the AADT relative to other variables.
- **Shoulder width:** The estimates indicate that wider shoulder width helps reduce collisions on HOV lanes.
- **Buffer width:** Coefficients for buffer widths show interesting findings, though they are not found to be statistically significant at least 10% in the model. For HOV lanes, buffer widths are positively associated with small magnitude; but for left lane, negatively associated with relatively large magnitude. This signifies that the buffer widths have greater effects on left lane than HOV lane.
- **Left lane width:** left lane widths were excluded in the estimated model due to their statistical insignificance (i.e. large standard errors) and the inference could not be drawn.
- **Length:** Since the features within each segment are homogeneous, the number of collisions within the segment is linearly correlated with the length of segment. Thus, the length of segment was specified as an offset variable (i.e. the coefficient was constrained to one) such that the impact of segment length is controlled.
- **Over-dispersion Parameter:** To test significance of over-dispersion parameters, likelihood ratio tests were performed and the over-dispersion parameters in all models, except injury collisions in HOV lane, were found to be significant, indicating evidence of over-dispersion and supporting the use of NB regression over Poisson regression.

TABLE 2 Estimated Coefficients

Variables	**Coefficient (Std. Err.)**
Property Damage Only (PDO) Collisions in HOV Lane, $E(C_{HOV}^{PDO} \mid x_{i,HOV})$	
HOV Lane Width (= 1 if 11 ft., = 0 otherwise)	-0.740 (-1.266)*
HOV Lane Width (= 1 if 11.5 ft., = 0 otherwise)	-1.001 (-1.365)**
HOV Lane Width (= 1 if 12 ft., = 0 otherwise)	-0.990 (-1.961)***
HOV Lane Width (= 1 if 12.5 ft., = 0 otherwise)	-1.637 (-1.526)***
HOV Lane Width (= 1 if 13 ft., = 0 otherwise)	-0.725 (-0.949)
HOV AADT (× 1,000)	0.033 (0.01)**
Ln(Shoulder Width (ft.))	-0.388 (-0.054)**
Buffer Width (ft.)	0.066 (0.064)
Over-dispersion parameter, 1/*y*	1.597 (-0.333)***
Log pseudo-likelihood at convergence:	-345.959
Injury Collisions in HOV Lane, $E(C_{HOV}^{Injury} \mid x_{i,HOV})$	
HOV Lane Width (= 1 if 11 ft., = 0 otherwise)	-1.266 (0.404)**
HOV Lane Width (= 1 if 11.5 ft., = 0 otherwise)	-1.365 (0.459)**
HOV Lane Width (= 1 if 12 ft., = 0 otherwise)	-1.961 (0.396)***
HOV Lane Width (= 1 if 12.5 ft., = 0 otherwise)	-1.526 (0.513)**
HOV Lane Width (= 1 if 13 ft., = 0 otherwise)	-0.949 (0.608)
HOV AADT (× 1,000)	0.010 (0.016)
Shoulder Width (ft.)	-0.054 (0.03)*
Buffer Width (ft.)	0.064 (0.072)
Over-dispersion parameter, 1/*y*	0.299 (0.319)
Log pseudo-likelihood at convergence:	-226.9486
Property Damage Only (PDO) Collisions in Left Lane, $E(C_{Left}^{PDO} \mid x_{i,Left})$	
Ln(Left AADT (× 1,000))	0.244 (0.037)***
Ln(Buffer Width (ft.))	-0.111 (0.103)
Over-dispersion parameter, 1/*y*	1.632 (0.180)***
Log pseudo-likelihood at convergence:	-728.909
Injury Collisions in Left Lane, $E(C_{Left}^{Injury} \mid x_{i,Left})$	
Left AADT (× 1,000)	-0.014 (0.006)**
Ln(Buffer Width (ft.))	-0.118 (0.106)
Over-dispersion parameter, 1/*y*	1.483 (0.264)***
Log pseudo-likelihood at convergence:	-453.995

*: Significant at 10%, **: Significant at 5%, ***: Significant at 1%

4. SELECTION OF CROSS-SECTIONAL DESIGNS

This section describes a procedure to find a set of geometric variables related to HOV facilities that can minimize expected number of collisions. The collision predictive models from the previous section can estimate the expected number of collisions for each injury and lane, given all the input variables. The expected numbers are expressed as following functions.

$$E(C_{HOV}^{PDO} \mid x_{i,HOV}) = e^{length-0.740x_{1i}-1.001x_{2i}-0.990x_{3i}-1.637x_{4i}-0.725x_{5i}+0.033x_{6i}} \cdot {x_{7i}}^{-0.388} \cdot e^{0.066x_{8i}}$$

$$E(C_{HOV}^{Injury} \mid x_{i,HOV}) = e^{length-1.266x_{1i}-1.365x_{2i}-1.961x_{3i}-1.526x_{4i}-0.949x_{5i}+0.010x_{6i}-0.054x_{7i}+0.064x_{8i}}$$

$$E(C_{Left}^{PDO} \mid x_{i,Left}) = e^{length} \cdot {x_{1i}}^{0.244} \cdot {x_{2i}}^{-0.111}$$

$$E(C_{Left}^{Injury} \mid x_{i,Left}) = e^{length-0.014x_{1i}} \cdot {x_{2i}}^{-0.118}$$

Where, subscripts and superscripts of C in left-side of the functions represent injury type and lane, respectively. x_i is an input (independent) variable for each segment i, and the numbers next to i indicate input variables sequentially numbered for each function as appeared in Table 1. Length is the segment length.

To find the set of geometric variables for the minimum number of collision frequency, the objective function and constraints are formulated below. The objective function is formulated to find minimum number of expected collisions while weighing injury collisions more due to its greater consequences and higher costs. Two constraints are i) the available total width is fixed and given, and ii) HOV lane widths can only be from 11 ft to 13 ft with 0.5 ft interval.

Objective function:

$$Min.\left(E(C_{HOV}^{PDO} \mid x_{i,HOV}) + E(C_{Left}^{PDO} \mid x_{i,Left}) + w \cdot \left\{E(C_{Left}^{Injury} \mid x_{i,Left}) + E(C_{HOV}^{Injury} \mid x_{i,HOV})\right\}\right)$$

Subject to:

total width$_i$ = buffer width$_i$ + HOV lane width$_i$ + shoulder width$_i$

HOV lane widths$_i$ = 11, 11.5, 12, 12.5, 13 ft

Where, w is a weighting factor for injury collisions.

For each freeway segment, total width and AADTs for HOV and left lanes are given or at least pre-determined based on the survey and detector measurements, respectively. Thus, the other geometric variables can be found by numerically solving the objective function with given constraints. The description of this procedure is furnished with an example in the following section.

5. CASE STUDY

To demonstrate the proposed methodology, 14-mile segment of Interstate 680 southbound, stretching from Alameda County to Santa Clara County in the San Francisco Bay Area, was selected for this case study. The stretch of freeway is under construction for converting its contiguous type HOV facility (peak-hour operation) to buffer-separated High-Occupancy Toll (HOT) facility (24-hour operation). Though its operational schemes change from HOV to HOT, its configuration after conversion is buffer-separated type and this corridor is well-suited for the demonstration of the methodology in this study.

Input data were extracted from inductive loop detector database and TASAS geometric database. For AADT data, peak-hour traffic count data from HOV and left lanes for whole year of 2008 were downloaded from PeMS and proportionately projected to AADT with temporal traffic patterns over the day. Total widths were calculated based on shoulder and lane widths information in TASAS geometric database. The weight factor, w, was determined by the ratio of average delay cost of PDO collisions to that of all other injury collisions (≈ 4.22) based on NHTSA report (*20*).

The map shown in Figure 2 displays cross-sections of current freeway segments in three location – post mile 7.5 in Alameda County, post mile 2.0 in Alameda County, and post mile 8.0 in Santa Clara County, and the proposed cross-sections by the method in this paper. These locations were selected because they composed most of the freeway stretch while cross-sectional designs of other remaining segments vary sporadically. For all three segments, 12-ft HOV lane width was selected and converting median shoulder widths to buffer widths was recommended. In addition, considering the availability of right-of-way and recommended cross-sectional designs, 17.3-ft is available for median shoulder in the second segment (post mile 2.0 in Alameda County) and, thus, the second segment can be used as enforcement area for HOV or HOT lane operation.

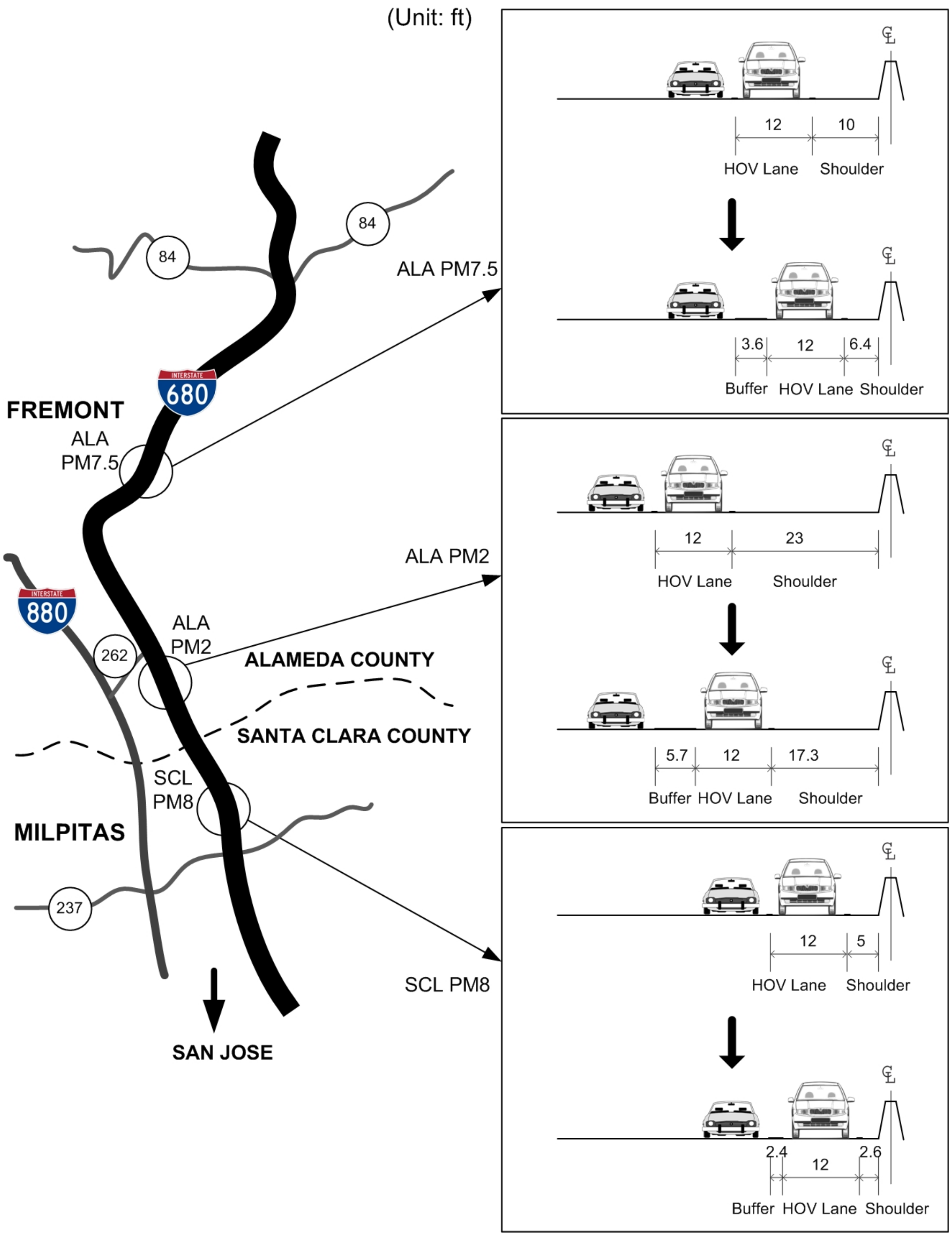

FIGURE 2 Converted Designs of HOV facility in Interstate 680 Southbound, San Francisco Bay Area

6. DISCUSSION

HOV facilities have been implemented to improve the overall mobility for congested freeway systems. To facilitate operations of traffic flows in HOV lanes, a substantial proportion of freeway segments with HOV lanes have utilized buffer zones to separate the HOV traffic from the congested non-HOV traffic in adjacent GP lanes – buffer-separated type of HOV lane. Since HOV facilities are generally deployed in crowded urban regions, it is often difficult to have sufficient right-of-way that can be converted to HOV lanes with a cross-sectional design that offers enhanced safety performance. Therefore, there is a strong incentive to establish supporting criteria and guidelines for selecting an optimal width for each design element by considering tradeoffs among median shoulder, HOV lane, and buffer widths.

This study proposes a quantitative method in selecting cross-sectional design for HOV facilities based on collisions and geometric attributes data. Firstly, the proposed methodology estimates collision predictive models for HOV and the adjacent GP (left) lanes by injury types. The outcome variable of each model is the number of collisions in each category and the independent variables are geometric attributes and AADT. Based on the models, thus, expected number of collisions can be predicted if independent variables are given. As a next step, an objective function is formulated as a sum of all the estimated models weighted by influential magnitude of injury types. Finally, the outcomes of objective function are searched through inputting all possible design variables to achieve the best safety performance.

The collision predictive models based on real-world collision data present statistically significant results. To exercise the applicability of the methodology, the models and the subsequent optimization method are applied to one actual corridor, Interstate 680 in the San Francisco Bay Area, where converting contiguous HOV to buffer-separated HOT lanes is underway as of the writing of this paper. This case study shows that the proposed methodology can be applied to compute the optimal cross-sectional design for buffer-separated facilities based on the current geometric variables.

The proposed method can provide the cross-sectional design for safety performance based on the quantitative evaluation of traffic safety in HOV facilities while flexibly incorporating other constraints that often arise in considering other aspects of planning and designing process of HOV facilities such as operational performance, environmental and construction costs, etc. These constrains can be included in the evaluation process by introducing them as constraints prior to searching minimum of the objective function.

In addition to cross-sectional design, buffer-separated HOV facilities have additional geometric variables to allow HOV maneuvers to enter and exit the HOV lane, ingress/egress sections – locations with respect to on- and off-ramps, length, its entering and exiting traffic volume. However, the present study did not attempt to include designs of ingress/egress sections in evaluating geometric attributes of HOV facilities. This needs to be further explored to complement designs for safety performance of buffer-separated HOV facilities. Also, it will be desirable to incorporate more data samples to confirm the significance of some coefficients in the models established in this study. These remain topics of future studies.

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