NCHRP Project 17-89A

Safety Prediction Model for Freeway Facilities with High Occupancy (HO) Lanes

Informational Guide

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Introduction

In an effort to relieve highway congestion and promote the movement of people, some State Departments of Transportation (DOTs) have modified their freeway facilities to include high-occupancy vehicle (HOV) lanes, high occupancy toll (HOT) lanes, and other managed-lane (ML) strategies. In their review of national trends related to ML facilities, Fuhs and Obenberger (2002) found that there were about 1,200 route-miles of HOV facilities and 50 route-miles of HOT facilities in 2001. These numbers increased to 1,800 route-miles of HOV facilities and 500 route-miles of HOT facilities by 2015 (Fitzpatrick et al, 2016). In 2021, Wood et al. (2021) developed an inventory of specialty lanes and highways located on non-signalized freeway systems that are not typically for general-purpose use. The inventory identified 2,875 lane-miles of HOV facilities and 1,141 lane-miles of HOT facilities. This guide refers to facilities with HOV and HOT as high-occupancy (HO) lane facilities. Figure 1 provides a graphical representation of States with a HO lane facility as of 2021.

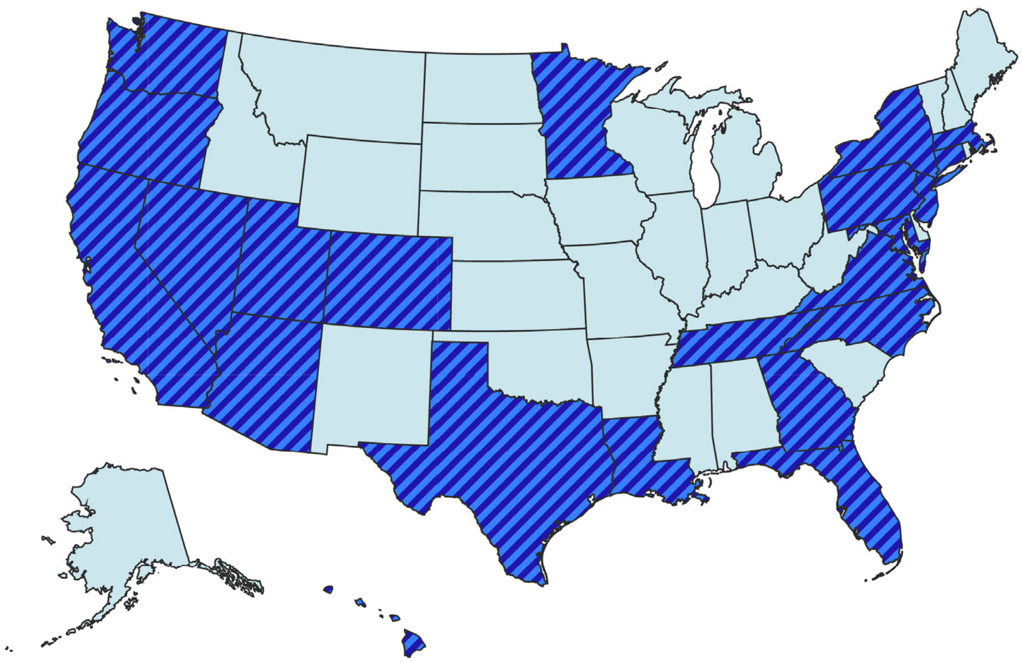
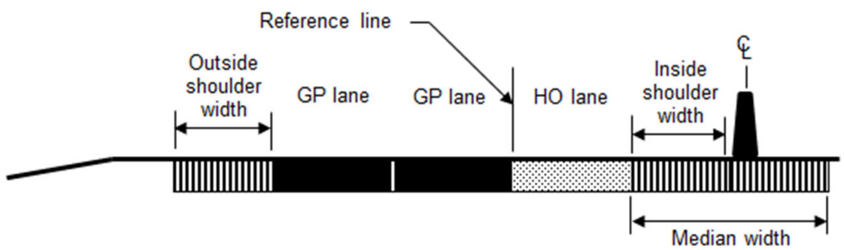


Figure 1. States with HO lane facility as of 2021.

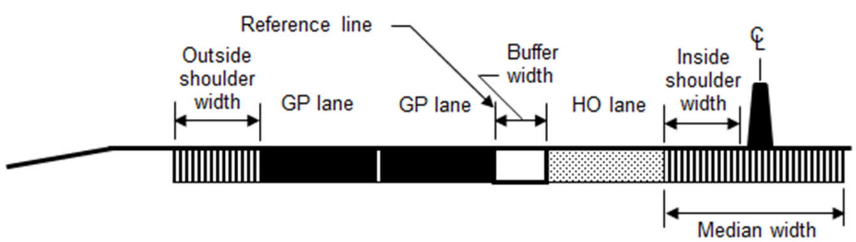
Fitzpatrick et al. (2016) define HOV lanes as MLs restricted to high occupancy vehicles with no tolling applied. The study estimated that about 85 percent of HOV facilities use a "2+" eligibility policy and about 50 percent of facilities operate on a time-of-day basis. Fuhs and Obenberger (2002) add that as a congestion management strategy, "HOV lanes have been widely applied in the United States to preserve mobility, maintain trip reliability, and improve the person-moving capability within a corridor or metropolitan area." Eisele et al. (2006) characterize HOT lanes as offering the option for vehicles to travel on HOV lanes for a fee when they would not normally meet the occupancy requirements of the lane. This allows for generation of revenue and provides a solution for concerns about underused HOV lanes. Taken together, this guide refers to facilities with HOV and HOT as high-occupancy (HO) lane facilities. This guide does not cover express toll lane or other toll facilities (i.e., facilities without an HO component).

Freeway facilities with HO lanes are generally defined as having one of three types of lateral separation. Figure 2 provides examples of each type of separation, including:

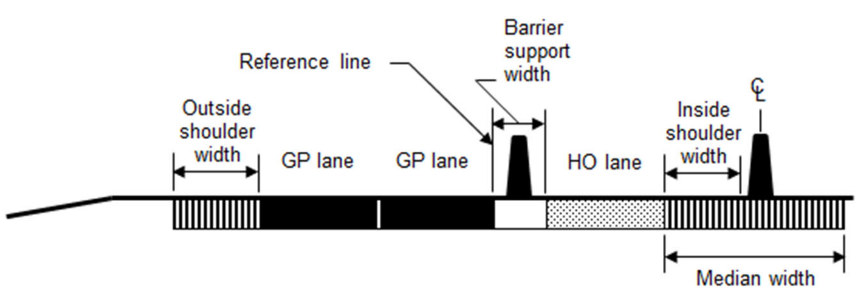
a. Lane line separation. Facilities with lane line separation generally provide continuous access between the leftmost general-purpose (GP) lane and the HO lane. Separation may include a single solid line or a broken line.
b. Buffer separation. Facilities with a buffer separation generally include multiple solid lines with a buffer space between. Generally, lane changes are not permitted (except at designated access points) but are not prevented by a physical barrier.
c. Barrier separation. Facilities with barrier separation may consist of longitudinal barrier or pylons, preventing vehicles from crossing between the leftmost GP lane and the HO lane except at designated access points.



a. Lane Line Separation



b. Buffer Separation



c. Barrier Separation

Figure 2. Measurement of cross section data elements.

HO Lane Facility Tradeoffs

This section provides an overview of the documented operational and safety performance of HO lane operation. The purpose of this section is to offer planners and engineers high-level details for understanding operational and safety performance tradeoffs for these facilities.

OPERATIONAL PERFORMANCE

Several studies have examined the operational performance of HO lanes relative to GP lanes as well as the operational performance of HO lanes by lateral separation type. The following summarizes research results related to both study types.

- Turnbull (2002) found that decreasing the vehicle-occupancy requirement on the El Monte Busway on the San Bernardino (I-10) Freeway from 3 or more persons per vehicle to 2 or more persons per vehicle resulted in reductions in travel speed (65 mph to 20 mph in the AM Peak) and a decrease in travel speed for GP lanes (25 mph to 23 mph in the AM Peak). Further, while the hourly HOV lane volumes increased from 1,100 to 1,600 during the morning peak period, the number of persons carried decreased from 5,900 to 5,200. Peak period travel times increased by 20 to 30 minutes.
- The Oregon Department of Transportation (2001) evaluated I-5 before and after HOV lane installation. The follow-up studies indicated that HOV lane drivers save an average of eight to ten minutes over the length of the corridor and the HOV lane carries approximately 2,600 people per hour relative a GP lane average of approximately 1,700 people per hour.
- Martin et al. (2004) found that during uncongested hours, HOV lanes on I-15 carried 52.2 percent fewer people and 76.3 percent fewer vehicles than GP lanes. During congested hours, the HOV lane carried the same number of people as a GP lane but with 56 percent fewer vehicles. Further analysis indicated a nearly 10 mph difference in speed between the HOV and GP lanes during the peak period, resulting in a 31 percent percent (7 minute) travel time savings.
- May et al. (2007) found that HOV lanes carried approximately 27 percent of peak hour, peak direction traffic while mixed-use lanes carried only 19 percent. Across all districts, the average HOV time savings for vehicles traveling the length of the HOV lanes was 6.7 minutes per trip.
- Cassidy et al. (2010) found that carpool lanes passing through bottlenecks significantly increase discharge flows in adjacent lanes. This effect was even found when carpool lanes are underutilized (with flow as low as 1,200 vehicles per hour), reducing both people delay and vehicle delay. The results suggest the smoothing effect can be quite large for narrow freeways with few total lanes.
- Several researchers have evaluated the operational effects of lateral separation type. Liu et al. (2011) examined the frictional effect between GP lane and ML operations with different separation types – concrete barrier, pylon, buffer, and stripe. This study verified the existence of a frictional effect between GP and HO lanes and found that separation type is the most significant characteristic affecting the friction intensity among others – operation strategy, number of lanes.
- Jang et al. (2012) examined the flow-density-speed relations for stripe-separated and buffer-separated (buffer width 2-4 ft) HOV lanes. By comparing the flow-density-speed

relations on HOV lanes at different adjacent GP lane speeds, they found that the adjacent GP lane speed has a significant effect on the relations for stripe-separated HOV facilities, which is consistent with the frictional effect findings in Liu et al. (2011). However, for buffer-separated HOV lanes, there is no distinctive pattern observed between the HOV lane traffic and adjacent GP lane speed, indicating that the influence of GP lane speed is either consistent or absent on the flow-density-speed relation in the buffer-separated HOV lanes.

- Avelar et al. (2016) collected traffic data at two sites in Houston, Texas to examine the operational performance between a buffer-separated ML with its neighboring GP lane. Both sites feature a buffer separating the single ML from the GP lanes, with one having plastic pylons (buffer width 4 ft) and the other having a painted buffer only (buffer width 2ft). The study found a significant association between the adjacent GP and ML speed. However, they found the presence of pylon may help reduce the influence of GP speed on ML operation.
- Built upon NCHRP project 15-49, Fitzpatrick et al. (2017) evaluated speeds on existing buffer-separated (and buffer with plastic pylon) HO lane facilities. Speed and volume data from approximately 130 unique sites were collected in California and Texas. The study confirmed that the HO lane volume and the GP lane speed are related to the speed in the HO lane. Increased volume and decreased speed in the neighboring GP lane have a negative effect on the operations of HO lane (i.e., are associated with a decreased speed). The amount of influence is a function of flush buffer characteristics. For example, for each 1 mph increase in speed on the GP lane when it is congested (density > 25 vpmpl), the speed on the ML increased by 0.03 mph for buffer or by 0.12 mph for buffer with pylons.
- Wu et al. (2015) proposed a framework for mobility performance comparison between different types of HOV facilities in terms of access control (limited access and continuous access). Results consistently showed that the HOV access type variable is statistically significantly associated with capacity across all models. The coefficients of HOV access type in all the models indicate that HOV lane with limited-access would have higher overall capacity than a continuous-access HOV facility.
- Cassidy et al. (2015a; b) studied the impacts of limited-access HO lanes on bottleneck production and the corresponding policy implications via empirical spatiotemporal analysis and simulation. Several freeway facilities with buffer separated HOV and HOT lanes from California and Minnesota were selected as example cases. They found that access points are prone to become bottlenecks and by removing the buffer, a new bottleneck would be triggered but its overall damage is less than what is caused by the access-point bottleneck.
- Shan et al. (2018) proposed a new access control type for HOV lanes called partially limited access, which allows continuous access on the majority of HOV lane sections, but a buffer is implemented on selected segments strategically. They selected a section of an HOV facility on SR-210 E in Southern California as a case study. For the partially limited access case, a buffer is placed immediately upstream of an off-ramp up to the gore point of the off-ramp. By comparing the simulation results across different scenarios, they found that the partially limited access control increased the throughput and decreased delay on the freeway, providing a higher overall network efficiency.

It is widely acknowledged that freeway geometric features, as well as the interactions between GP lanes and HO lanes, can impose a variety of impacts on the HO lanes' operational performance. The extent of such impact depends on the parameters chosen along the freeway segments, as well as the traffic operation conditions.

Highway Capacity Manual 6th edition (HCM6) presents tools for evaluating the operational effects of ML facilities and a methodological framework for conducting detailed capacity assessment (Elefteriadou, 2016). The analysis procedure builds upon the core HCM uninterrupted flow methodology's segment classification, and divides ML facilities into four types of segments: ML merge and diverge, ML weaving, ML access, and basic freeway segments. It is found that the composition, free-flow speed, capacity and behavior characteristics of ML traffic streams are different from those of GP lanes. And most importantly, the interactions between the two lane groups (GP and ML) are observed. Two interactions and their associated effects on operations are quantified:

1. Cross-weave friction effect

This is when MLs have intermittent at-grade access from the GP lanes, and a cross-weave movement might occur when a vehicle enters the freeway from an on-ramp, and has to cross multiple GP lanes to reach the ML access (and vice versa). Such cross-weave effect is applied to the GP segments upstream (or downstream) of the ML access point in the form of an adjustment factor to GP segment capacity. This factor is a function of cross-weave demand, cross-weave length, and the number of GP lanes.

2. Adjacent friction effect

Friction effect is observed and quantified in HCM6 as ML operations are affected by the high GP traffic densities, especially in cases where no physical separation exists between the two lane groups (GP and ML). For lane line- or single-lane buffer-separated ML facilities, a friction-constrained speed prediction model is used to estimate ML speeds. When the GP lanes operate below the specific density threshold (35 pc/mi/ln), a non-friction-based speed prediction model is used.

SAFETY PERFORMANCE

Much of the previous research on freeways with ML facilities focused on the safety impacts of adding MLs to existing facilities. Historically, researchers focused on comparing crash rates for facilities before and after ML installation, with comparisons being separated by access type and buffer type. Table 1 provides a summary of research on safety effects of HOV lane installation by lateral separation type, number of lanes, and restriction type.

Table 1 reveals that researchers generally found higher crash rates and frequency after the installation of the managed lane, regardless of access type and buffer type. However, research results are not consistent on the relative safety impacts of limited vs. continuous access MLs. Researchers have indicated that access type may be dictated by the needs of a facility and limited access and continuous access ML facilities generally serve different purposes (therefore, comparing crash frequency across these access types may be an applies to oranges comparison). Additionally, in general, freeways with limited access MLs have 24-hour access restriction, while continuous access ML facilities are generally restricted during the peak periods and revert to mixed-use lanes in the off-peak periods.

Table 1. Summary of research on safety effects by lateral separation type.

Study	Separation Type	HOV Lanes	Restriction	Percent Change in Crashes
Miller et al. 1979	Separate HOV Facility (Barrier)	1 Directional	Bus-Only and Bus/3+	50% increase in PM Peak; 14% decrease in daily
	Separate HOV Facility (Posts)	1 Directional	Bus-Only and Bus/3+	58% increase in AM Peak; 30% increase in PM Peak; 33% decrease in daily
	Concurrent HOV Facility	1 Directional	Bus-Only and Bus/2+	53% decrease to 265% increase in peak; 41% decrease to 157% increase in daily
Golob et al. 1990	Buffer-Separated HOV Facility (8-inches)	1 Directional		2% increase
Skowronek et al. 2002	Contraflow Movable Barrier HOV Facility	1 Directional	Bus/2+	No change in injury crashes
	Buffer-Separated HOV Facility (2.5 feet)	1 Directional	Bus/2+	50% increase injury crashes; 48% increase peak period
	Buffer-Separated HOV Facility (3 feet)	1 Directional	Bus/2+	43% increase injury crashes; 55% increase peak period
Cothron et al. 2004; Cooner and Ranft 2006	Contraflow Movable Barrier HOV Facility	1 Directional	Bus/2+	No change in injury crashes
	Buffer-Separated HOV Facility (2.5 feet)	1 Directional	Bus/2+	56% increase injury crashes; 67% increase peak period
	Buffer-Separated HOV Facility (3 feet)	1 Directional	Bus/2+	41% increase injury crashes; 56% increase peak period
Bauer et al. 2004	Unknown Separation	1 Directional	Unknown	7% increase with 4 GP lanes; 6% increase with 5 GP lanes
Cooner and Ranft 2006	Buffer-Separated HOV Facility (2.5 feet)	1 Directional	Bus/2+	153% increase injury crashes in leftmost GP lane
	Buffer-Separated HOV Facility (3 feet)	1 Directional	Bus/2+	188% increase injury crashes in leftmost GP lane
Fitzpatrick and Avelar 2016	Pylon Buffer Type (Relative to Flush Buffer	1 Directional	Unknown	94% increase in total freeway crashes

Additionally, researchers have examined the safety impacts of converting facilities with an HOV lane to an HOT lane. Cao et al. (2012) studied the conversion of I-394 from HOV lanes to HOT lanes in Minnesota. An empirical Bayes analysis indicated a 5.3 percent reduction in crashes after conversion. The authors indicated that the improvement was likely due to the change from continuous access to limited access points as well as increased use of the facilities relative to their status as HOV lanes. The authors cautioned that these factors limit the generalizability of the findings.

Araque (2013) found that weaving between (limited access) MLs and GP lanes increased after conversion to HOT lanes. Weaving was used as a surrogate for increased weaving being associated with reduced safety performance. He noted that the number of access points were reduced from 15 to 9 along the corridor through the conversion to HOT lanes, but drivers were more likely to weave out of the HOT lane to the GP lanes when the GP lane was moving at a higher speed, indicating that drivers are likely not willing to pay for HOT lanes unless a clear benefit is observed. Additionally, restriping for the HOT lane nearly eliminated illegal weaving activity.

Abuzwidah and Abdel-Aty (2017) examined the safety impacts of conversion from HOV facilities to HOT facilities on Interstate 95 in Florida. The results indicated conversion from HOV to HOT facilities does not impact the overall safety of the roadway segments. They found that all crash categories were reduced for HOT-lane segments while all crash categories increased on the GP lanes. The two competing impacts essentially canceled out.

Predictive Safety Analysis for Freeways with HO Lanes

NCHRP Project 17-89A developed a method for predicting crash frequency and severity (Himes et al. 2021a) for directional freeway segments with HO lanes (as opposed to a bi-directional approach predicting crash frequency for both freeway directions combined). For this research, the project team developed proposed text for a future edition of the Highway Safety Manual (HSM) as well as a companion safety implementation guide (Himes et al. 2021b). The safety implementation guide provides specific details on implementing the predictive method as well as details on using the accompanying spreadsheet implementation tool. This section provides a brief overview of pertinent details for conducting predictive safety analysis for freeway facilities with HO lanes.

PREDICTIVE METHOD APPLICABILITY

Table 2 identifies a wide range of HOV and HOT design configurations and their application frequency on freeways with HO lanes. The possible design configurations are indicated in the last four columns of the table using the various combinations of lateral separation, access type, and lane orientation. Those combinations that are associated with a cell having a white background are addressed by the predictive method. Those combinations associated with a cell that has a grey shaded background are not currently addressed by the predictive method.

The predictive method does not differentiate between HOV and HOT operation. The HO lanes must be located to the left of the GP lanes and have one the design configurations listed in Table 2. The predictive method can be used to evaluate projects adding an HO lane to an existing freeway, so long as both the predictive method for traditional freeway segments (as described in Chapter 18 of the HSM) and the predictive method for freeway segments with HO lanes are both calibrated. Further, the predictive method is applicable for weaving section analysis and alternative cross-section analysis.

Table 2. HOV and HOT lane design configurations and application frequency.

Lateral Separation	HOV and HOT Access Type	HOV and HOT Application Frequency by Lane Orientation [a, b]			
		Concurrent Lane	Separate Roadway	Reversible Lane	Contraflow Lane
Lane line	Continuous (dashed)	Often used; addressed by method	—	—	—
	At-grade entrance and exit zones	Often used; addressed by method	—	—	—
Flush buffer	Continuous (dashed)	Occasionally used	—	—	—
	At-grade entrance and exit zones	Often used; addressed by method	—	—	—
Pylon buffer	Grade-separated entrance and exit points	—	Often used	—	—
	At-grade entrance and exit zones	Often used; addressed by method	—	—	Often used
Barrier	Grade-separated entrance and exit points	—	Often used	Often used	—
	At-grade entrance and exit zones	Often used; addressed by method	—	Often used	Often used

[a] Predictive method addresses combinations associated with a cell having a white background.
[b] "—" identifies combinations not used (or rarely used).

DATA REQUIREMENTS

This section identifies the input data needed for the predictive method. These data represent the geometric design features, traffic control features, and traffic demand characteristics that have been found to have some relationship to crash potential. Further details on input data definitions and measurements can be found in Section 2.5.2. of the NCHRP 17-89A HOV/HOT Safety Implementation Guide (Himes 2021b). Input data include the following:

- Number of GP through lanes.
- Number of HO lanes (at speed-change lane sites).
- Length of freeway segment and length of speed-change lane.
- Presence of horizontal curve.
- Speed limit.
- Width of buffer, outside shoulder, inside shoulder, and median.
- Length of barrier in the median and in the roadside.
- Presence of a one-sided Type C weaving section.
- Distance to nearest upstream entrance ramp.
- Distance to nearest downstream exit ramp.
- Proportion of hours where the lane volume exceeds 1,000 vehicles per hour per lane.
- Freeway AADT volume.
- Entrance and exit ramp AADT volume.
- HO lane access restriction by time of day.
- Distance form the last HO lane egress point to the next exit ramp.
- Average speed differential between the inside GP lane and the HO lane(s).

KEY PREDICTIVE METHOD RELATIONSHIPS

There are several key relationships from the predictive method for freeway facilities (including speed change lane segments) with HO lanes, including the following:

- Compared to a base condition of a lane line lateral separation type, narrow flush buffers (approximately less than 3.5 feet) are associated with an increase in total crash frequency, while wider flush buffers are associated with a decrease in total crash frequency.
- Compared to a base condition of a lane line lateral separation type, pylon and barrier lateral separation are associated with a decrease in total crash frequency.
- For facilities with lane line lateral separation and flush buffer separation, total crash frequency is expected to increase as the speed differential between the HO lane and the left-most GP lane increases.
- For speed change lane segments, the presence of two or more HO lanes is associated with higher total crash frequency.
- For facilities with access to and from HO lanes and the GP lanes via at-grade entrance and exit points, shorter distances from the HO lane access point to the nearest downstream right-side exit gore are associated with higher total crash frequency.
- The presence of a Type C weaving section is associated with higher total crash frequency.

There are also several key relationships between geometric elements and crash outcome severity. The following summarizes those for freeway facilities (including speed change lane segments) with HO lanes.

- Higher posted speed limits are associated with an increased probability of more severe crash outcomes.
- Facilities with at-grade entrance and exit zones are associated with less severe crash outcomes.
- Facilities with median and outside barrier are associated with a decreased probability of fatal and serious injury crash outcomes.
- Facilities with 24-hour access restriction are associated with an increased probability of more severe crash outcomes.
- Facilities with a higher proportion of horizontal curves are associated with an increased probability of more severe crash outcomes.

PREDICTIVE METHOD LIMITATIONS

The predictive method does not account for the influence of the following conditions on crash potential:

- Freeways in rural areas.
- Freeways with managed lanes other than HOV or HOT lanes (e.g., truck-restricted lanes, truck-only lanes, or bus-only lanes).
- Freeways with eight or more GP through lanes in the subject travel direction.
- Freeways where HOV or HOT lanes are accommodated (a) a separate roadway, (b) a reversible lane, or (c) a contraflow lane.
- Freeways with concurrent HOV or HOT lanes with a flush buffer and continuous access.

- Freeways with HOV or HOT lanes that are accessed by grade-separated entrance/exit points.
- Freeways with part-time shoulder use or bus-on-shoulder operation.
- Shoulder rumble strip presence.
- Ramp metering.
- Toll plazas.
- Work zone presence.
- Speed-change lanes that provide left-side access to the freeway.

The predictive method does not distinguish between barrier types (i.e., cable barrier, concrete barrier, guardrail, and bridge rail) in terms of their possible unique influence on crash severity.

IMPLEMENTATION SPREADSHEET

The NCHRP Project 17-89A project team developed a spreadsheet implementation tool to support analysts predicting safety performance for freeway facilities with HO lanes. The spreadsheet tool directly implements all aspects of the predictive method and provides users an indication of required data, data bounds, and when possible incorporates selection menus instead of open-ended inputs. The spreadsheet tool provides users with the option to input calibration factors or override default distributions to improve predictive performance for their jurisdiction. Additionally, the spreadsheet tool incorporates user-provided information on historic crash frequency to compute expected crash frequency. The spreadsheet tool can handle up to 20 segments in one file and includes a summary tab to combine results for all segments for which data were input.

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